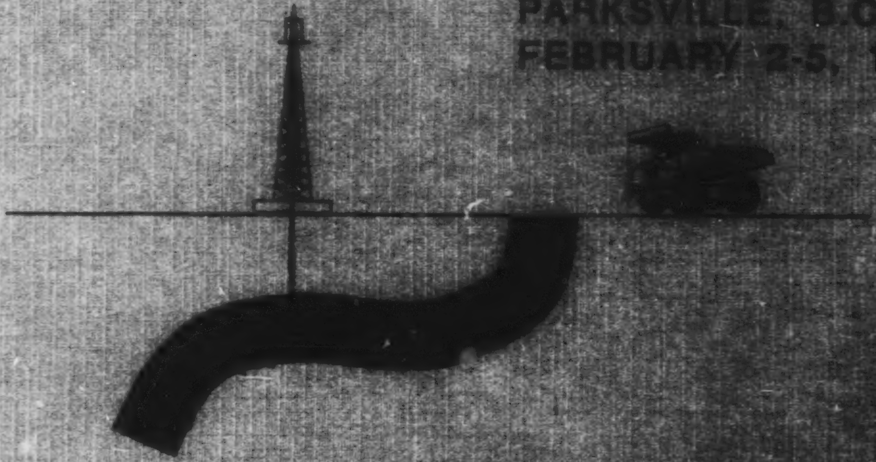
THE CANADIAN COAL
and
COALBED METHANE
GEOSCIENCE FORUM

PARKSVILLE, B.C.
FEBRUARY 2-5, 1992



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PROCEEDINGS

CANADIAN COAL AND COALBED METHANE GEOSCIENCE FORUM

Parksville, British Columbia

February 2 - 5th 1992

FORUM PROCEEDINGS

Compiled by:..Barry Ryan and John Cunningham

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INTRODUCTION

The Canadian Coal and Coalbed Methane Geoscience Forum and its predecessor, the Western Canada Coal Geoscience Forum is held periodically in a western Canadian centre. The forum is intended to provide a venue for people involved in coal science in the broadest sense, to present their work and exchange ideas. These people are drawn from diverse backgrounds representing mining, universities, geological surveys, and consultants. Interests cover the gamut from fundamental coal science to coalbed methane, to day to day problems in the mining and marketing of coal.

An attempt has been made to ensure that all interests are represented in the papers and abstracts presented in this volume and at the conference. The value of a conference is, in part, the chance to attend the presentation of papers of specific interest, and also the chance to participate in the synergy that evolves when people meet who have diverse experiences linked by a common thread.

The papers and abstracts presented in this volume have not been subjected to external review. Each author was asked to ensure that his or her paper was informally reviewed by a colleague before submission.

The volume is organized under the following headings:

1) Coalbed Methane papers and abstracts
2) Coal Industry papers and abstracts
3) Coal Science papers and abstracts
4) Index to authors

Within each section the papers and abstracts are organized alphabetically by first authors.

Finally the technical committee would like to thank all the authors, who by taking the time to provide high quality papers and abstracts, have made the publication of these proceedings possible.

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CONTENTS

PAPERS AND ABSTRACTS

PAGE	AUTHOR (s)	AFFILIATION/TITLE

1 COALBED METHANE

3	W.B. Ayers W.R. Kaiser	Taurus Exploration, Inc. Alabama Bureau of Economic Geology, University of Texas *Coalbed methane occurrence and producibility, Fruitland Formation, Navajo Lake area San Juan Basin New Mexico*
21	K.M. Banks	Roke Oil Enterprises Ltd. Calgary *Quad neutron logs and coalbed methane*
23	J.C. Campbell A.R. MacLean D.L. Granatstein	Cape Breton Development Corporation, Nova Scotia Cape Breton Development Corporation, Nova Scotia Nova Scotia Power Corporation, Nova Scotia *Utilization alternatives for coalbed methane from the Sydney Coalfield in Nova Scotia*
39	R. Cech J.D. Carlson R.K. MacLeod	Sproule Associates Limited Calgary Sproule Associates Limited Calgary Sproule Associates Limited Calgary *Economics of Coalbed methane projects in the Western Canadian Basin*
57	F.M. Dawson J.T. Clow	Institute of Sedimentary and Petroleum Geology, Calgary Western Atlas Canada Ltd., Calgary *Coalbed methane research southeast British Columbia*
73	J. Ellard R. Roark	Taurus Exploration Inc., Alabama Taurus Exploration Inc., Alabama *Coalbed methane production from the Pottsville Formation at Cedar Cove Field Black Warrior Basin, Alabama U.S.A.*
85	D.G.S. Johnson L.A. Smith	LAS Energy Consultants, Calgary LAS Energy Consultants, Calgary *Coalbed methane in southeast British Columbia and structure of the Crowsnest Coalfield (Fernie Basin)*
87	M.N. Lamberson R.M. Bustin	Geology Department, University of British Columbia Geology Department, University of British Columbia *Coalbed methane characteristics of Gates Formation lithotypes, northeastern British Columbia*
103	W. Langenberg	Alberta Research Council *Geology and Coalbed methane potential of the Foothills in the Cadomin area, Alberta*

117	L. Lottman-Craigg	GeoMet Inc., Ashburn, VA
	P. Malone	GeoMet Inc., Ashburn, VA
		A method of fracture analysis to optimize coalbed methane production
119	M. Mavor	Resource Enterprises Inc., Salt Lake City, Utah
		Evaluation of coalbed natural gas open hole cavity completion productivity
141	S.P. Pappajohn	Carbon Energy International, Kent, Washington
	J.P. Jurius	Carbon Energy International, Kent, Washington
		Otimization of geotechnical and economic factors influencing coalbed methane exploration projects
143	B.A. Rottenfusser	Alberta Research Council, Edmonton
	R.J.H. Richardson	Alberta Research Council, Edmonton
		Coal bed methane reasearch at the Alberta Geological Survey
145	J. Rowling	Petroleum Geology Branch, Victoria
		Coalbed methane resources in British Columbia
147	L.A. Smith	LAS Energy Consultants, Calgary
	J.C. UnKauf	LAS Energy Consultants, Calgary
	D.G.S. Johnson	LAS Energy Consultants, Calgary
	E.J. Allen	LAS Energy Consultants, Calgary
		Coalbed methane potential in northeast British Columbia
149	M. Whiticar	University of Victoria
		Stable Isotope geochemistry of coals, humic Kerogens and related natural gases

2 COAL INDUSTRY

175	J. Briker	Alberta Research Council, Devon
	W. Pawlak	Alberta Research Council, Devon
	K. Szymocha	Alberta Research Council, Devon
	J. Kramer	Alberta Research Council, Devon
	B. Ignasiak	Alberta Research Council, Devon
		Air pollution control by application of AGLOFLOAT process for cleaning high sulphur bituminous coals
187	P. Gilmar	Westar Mining, Sparwood B.C.
		Westar Mining's Balmer Operations Coal Quality Control
189	M.E. Holuszko	B.C. Geological Survey Branch, Victoria
		Washability of Peace River and East Kootenay coals
211	M.E. Holuszko	B.C. Geological Survey Branch, Victoria
		Washability of British Columbia coals
213	A. Peach	Byron Creek Collieries, Sparwood B.C.
	J. Henderson	Geo-Pysi-Con, Calgary
		Coal planning and surface geophysics at Coal Mountain

229	H. Stellmach	Line Creek Resources, Calgary
		Utilization of Western Canadian Metallurical Coals
231	N.H. Wade	Monenco Limited, Calgary
	T.C. Lam	Monenco Limited, Calgary
		Using geophysical logs to predict geotechnical parameters in surface mines

3 COAL SCIENCE

243	H.J. Abercrombie	Institute of Sedimentary and Petroleum Geology, Calgary
	K. Burchard	Institut für Geologie Bern
	W. Kalkreuth	Institute of Sedimentary and Petroleum Geology, Calgary
		Coalbed methane potential of selected Kootenay coals in relation to petrographic and mineralogic characteristics
245	A.P. Beaton	Department of Geology University of Western Ontario
	A.R. Cameron	Institute of Sedimentary and Petroleum Geology, Calgary
	F. Goodarzi	Institute of Sedimentary and Petroleum Geology, Calgary
		Characterization of Yukon coals
265	R.A. Benkis	Monenco Limited, Calgary
		An overview of some selected coal resources of the world
291	G. Capobianco	Coal Association of Canada, Calgary
		Coal and the Environment
293	C.G. Cathyl-Bickford	Westwater Mining Ltd., Calgary
	R. Wilson	Westwater Mining Ltd., Calgary
	G. Hoffman	Westwater Mining Ltd., Calgary
		Geology mineability and coalbed gas potential of the Douglas Coal Zone in the Nanaimo Coalfield, Vancouver Island
311	J. Cunningham	B.C. Geological Survey Victoria
	B. Sprecher	B.C. Geological Survey Victoria
		Peace River Coalfield digital mapping program
313	F. Goodarzi	Institute of Sedimentary and Petroleum Geology, Calgary
	J. Calder	Nova Scotia Department of Mines and Energy, Nova Scotia
		Geochemistry of Carboniferous coals from Springfield Coalfield, Nova Scotia
315	F. Goodarzi	Institute of Sedimentary and Petroleum Geology, Calgary
	D.A. Grieve	B.C. Geological Survey Branch, Victoria
	D.A. Cameron	Insitute of Sedimentary and Petroleum Geology, Calgary
	A.R. Beaton	Department of Geology University of Western Ontario
	M. Labonte	Institute of Sedimentary and Petroleum Geology, Calgary
		Geochemistry of coals and associated sedimentary rocks from the Elk Valley Coalfield British Columbia, Canada
317	F. Goodarzi	Institute of Sedimentary and Petroleum Geology, Calgary
	M. Sadre	Department of Geology University of Western Ontario
	A. Matheson	B.C. Geological Survey Branch, Victoria
		Geochemistry of Bowron River coal deposit, British Columbia

319	F. Goodarzi D.J. Swaine	Institute of Sedimentary and Petroleum Geology, Calgary CSIRO Division of Coal and Energy Technology, Australia *Geochemistry of Boron in Coal*
333	A.C. Grant	Atlantic Geoscience Centre, Dartmouth, Nova Scotia *Seismic character of coal measures, Gulf of St Lawence region*
35	D.A. Grieve	B.C. Geological Survey Branch, Victoria *Phosphorus in British Columbia coking coals*
355	D.A. Grieve	B.C. Geological Survey Branch, Victoria *Relationships between coal quality parameters in British Columbia coals*
357	J.D. Hughes	Institute of Sedimentary and Petroleum Geology, Calgary *G.I.S. and three-dimentional CAD applied to computer-modelling of coalfields*
359	P. Jahans	University of Alberta *Pine Valley mapping and compilation*
361	C. Kenyon C.G. Cathyl-Bickford	B.C. Geological Survey Branch, Victoria Westwater Mining Ltd., Calgary *Geology of the Quinsam Coalfield*
363	W. Kilby	B.C. Geological Survey Branch, Victoria *Digital mapping-tools*
365	R.D. Naylor J.H. Calder T.A. Martel R.J. Ryan	Nova Scotia Department of Natural resources Nova Scotia Department of Natural resources Department of Earth Sciences, Oxford University, Oxford Nova Scotia Department of Natural resources *Controls on formation of Upper Carboniferous coals in the intermontane Stellarton and Cumberland Basins of Atlantic Canada*
399	K. Pratt W.D. Kalkreuth D.L. Marchioni M. Steller	Institute of Sedimentary and Petroleum Geology, Calgary Institute of Sedimentary and Petroleum Geology, Calgary Petro-Logic Services, Calgary Deutsche Montantechnologie, Essen, Germany *Petrographic examination of coal lithotype samples from the Lower Cretaceous Gates formation: a comparison of automated image analysis versus manual microscopy*
401	R.J.H. Richardson D.K. Chao C.W. Langenberg D. Fietz	Alberta Research Council, Edmonton Alberta Research Council, Edmonton Alberta Research Council, Edmonton Elad Enerprizes, Calgary *Coal compilation project geoscience information system (GSIS) suported coal resource mapping in Alberta*

411 R.J.H. Richardson Alberta Research Council, Edmonton
D. Nicols Alberta Research Council, Edmonton
Coal geoscience program; Alberta Geological Survey

413 B.D. Ryan B.C. Geological Survey Victoria
Coalbed Methane resource potential and coal washability at the Telkwa coal deposit central British Columbia

415 B.D. Ryan B.C. Geological Survey Victoria
Potential Coke strength after reaction of British Columbia coals

417 E. Van der Flier-Keller University of Victoria
Rare Earth Element patterns in seven western Canadian coals

433 Author Index

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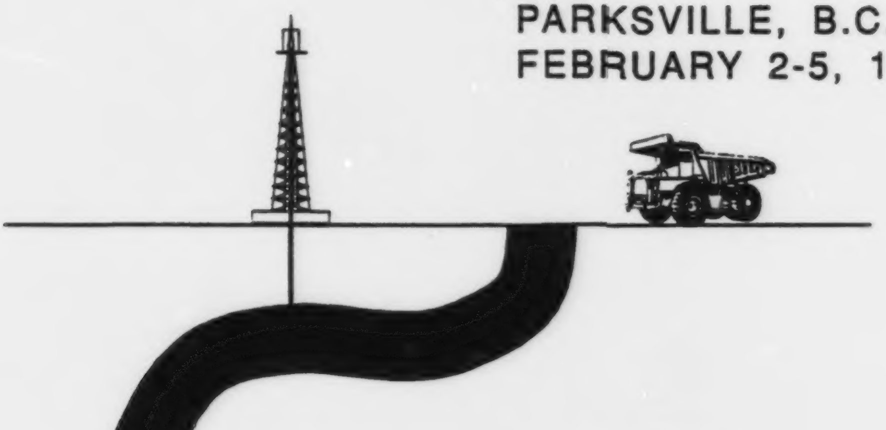

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PROCEEDINGS

1

COALBED METHANE PAPERS AND ABSTRACTS

NOTES

COALBED METHANE OCCURRENCE AND PRODUCIBILITY, FRUITLAND FORMATION, NAVAJO LAKE AREA, SAN JUAN BASIN, NEW MEXICO

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ABSTRACT

The most productive coalbed methane wells in the United States, those in the Navajo Lake area of the San Juan Basin, produce as much as 425 Mm^3/d (15 000 Mcf/d^3). To identify controls on the occurrence and producibility of Fruitland coalbed methane, we compared geologic and hydrologic maps to production trends.

The coal-bearing Fruitland Formation is a coastal plain unit that was deposited southwest of a northwest-trending, wave-dominated shoreline recorded in the Pictured Cliffs Sandstone. During Late Cretaceous time, the Pictured Cliffs shoreline migrated northeastward, crossing a structural hingeline. Higher subsidence rates north of this hingeline created additional accommodation space and initiated a shoreline stillstand that resulted in aggradation of coastal plain facies, including peat (coal) swamps. In coal depocenters, 8 to 14 seams form a northwest-trending deposit in which net-coal thickness exceeds 21 m (70 ft). Within the depocenters, many individual coal beds are laterally continuous in the paleostrike (northwest) direction, but they thin, or in some cases terminate, where they interfinger with coeval, northeast-trending, fluvial sandstone complexes; individual coal beds are thickest in floodbasin settings, between fluvial complexes.

In the Navajo Lake area, coal beds are the major Fruitland aquifers, and their geometry and extent control hydrologic and reservoir conditions. Recharge occurs primarily at elevated outcrops in the Hogback Monocline at the northern margin of the basin. Under high head created by the elevated recharge area, ground water moves down the steeply dipping north-basin flank and across the nearly flat basin floor to a postulated no-flow boundary along the structural hingeline. The no-flow boundary is caused by southwestward pinch-out of the thick, northwest-trending coal beds, by offset of the coal beds along faults at the hingeline, or both. The Fruitland Formation is regionally overpressured in the northern San Juan Basin due to artesian conditions. In most of the Navajo Lake area, simple pressure gradient is greater than 9.80 kPa/m (0.43 psi/ft), and locally, it exceeds 14.25 kPa/m (0.63 psi/ft).

Coalbed methane wells in the Navajo Lake area commonly produce 8.5 to 85 Mm^3/d (300 to 3 000 Mcf/d), but highly productive gas wells produce 282 to 425 Mm^3/d (10 000 to 15 000 Mcf/d). High permeability combined with significant contribution from conventionally trapped free gas and dissolved gas are postulated to explain exceptionally high production rates in this area. Highly productive wells occur in northeast-trending patterns that may reflect fractures trends, anomalously thick coal beds, Fruitland channel-fill sandstones, or a combination of all three.

INTRODUCTION

OBJECTIVES

The Navajo Lake area encompasses 557 km^2 (215 mi^2) in northern San Juan and Rio Arriba Counties, New Mexico (Figure 1) and includes some of the thickest coal beds in the San Juan Basin. Moreover, this area, which has a history of coalbed methane production extending from the early 1950's, also has the most productive coalbed methane wells in the United States. The objectives of this study were to (1) evaluate the structural controls on depositional systems, (2) delineate depositional systems and define their controls on the occurrence, trends, and continuity of coal beds, (3) identify structural features that may enhance coal permeability or affect coalbed continuity and, hence, fluid migration, and (4) relate coalbed methane production and reservoir conditions to the geologic and hydrologic settings.

METHODS

Geologic and hydrologic controls on coalbed methane occurrence and producibility commonly are complex. Therefore, we used a detailed database to study these controls at Navajo Lake. The primary database was approximately 400 geophysical well logs from oil and gas tests. Geophysical logs were used to make interlocking cross sections, and all remaining logs were correlated to those sections. Structure, isopach, lithofacies, and coal data from the logs were tabulated in computer files and were used to make computer-contoured maps and to post data for hand contouring. The cross sections and maps were then evaluated individually and were compared to maps of initial gas and water production to interpret geologic controls on the occurrence and producibility of coalbed methane.

REGIONAL GEOLOGIC SETTING AND STRATIGRAPHY

During Late Cretaceous (Campanian) time, the region of the present San Juan Basin was located on the western margin of the Western Interior Seaway (Figure 2). This coastline migrated northeastward, resulting in deposition of a vertical succession of shelf (Lewis Shale) through coastal (Pictured Cliffs Sandstone) to coal-bearing continental sediments (Fruitland Formation) (Figure 3). The contact between the Pictured Cliffs Sandstone and the Fruitland Formation, the massive coastal sandstone complex below the lowermost Fruitland coal, is time-transgressive because the shoreline migrated basinward (Figures 3 and 4). The conformable contact between the Fruitland Formation and the Kirtland Shale (Campanian/Maestrichtian) is a high-conductivity peak that occurs in a shale at the top of an upward-fining Fruitland sequence (Figure 3). We conclude that the basal Kirtland Shale is a regionally extensive unit that formed as a consequence of a short-lived marine transgression over the Fruitland coastal plain. The remainder of the Kirtland Shale is composed of continental sediments. The Kirtland Shale is unconformably overlain by the fluvial Ojo Alamo Sandstone (Paleocene).

STRUCTURAL SETTING

Structural activity impacted the availability and producibility of coalbed methane in four ways (1) syndepositional structural activity influenced depositional systems and, hence, coal occurrence; (2) the structural development of the San Juan Basin affected the burial depth and thermal maturity of Fruitland coal seams; (3) structural deformation caused faults that may offset the coal beds (reservoirs), forming barriers to flow; and (4) structural deformation resulted in minor folds that form structural traps, and fractures associated with these folds may enhance coalbed permeability.

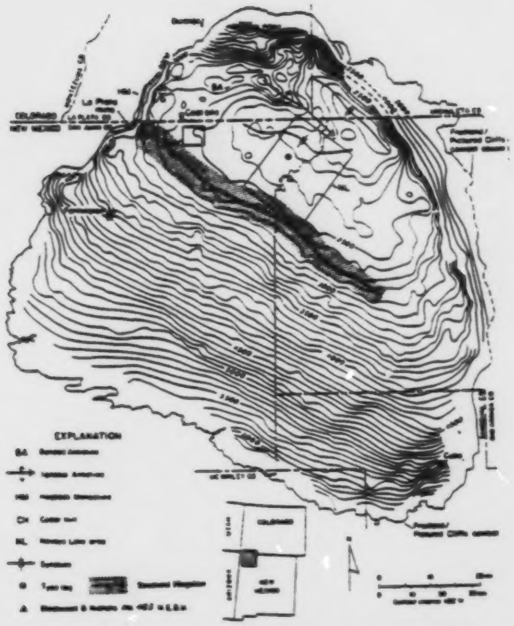
EXPLANATION
COLORADO
NEW MEXICO

Figure 1. Structure map of the Huerfanito Bentonite Bed of the Lewis Shale, San Juan Basin, showing location of the Navajo Lake area. A major synclinal axis crosses the northern part of the Navajo Lake area. Ignacio Anticline is north of this syncline. Along the northern and eastern margins of the basin, strata dip steeply basinward (Hogback Monocline).

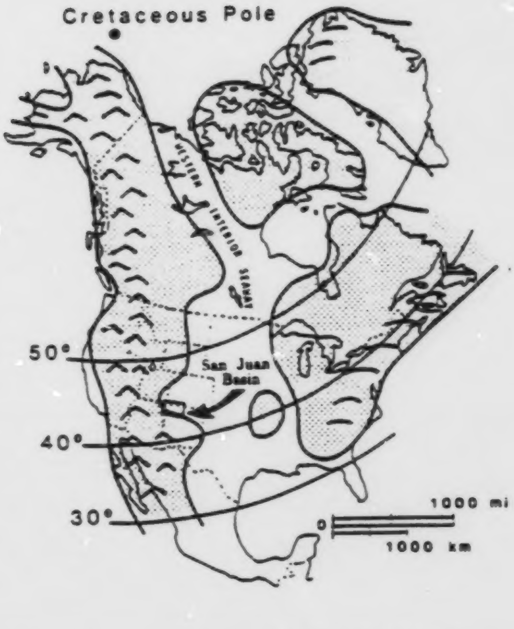
Cretaceous Pole
WESTERN INTERIOR SEAWAY
San Juan Basin
50°
40°
30°
0
1000 mi
1000 km

Figure 2. Location of the San Juan Basin relative to the Western Interior Seaway. Modified from Palmer and Scott (1984) after Williams and Steick (1975) and Irving (1979).

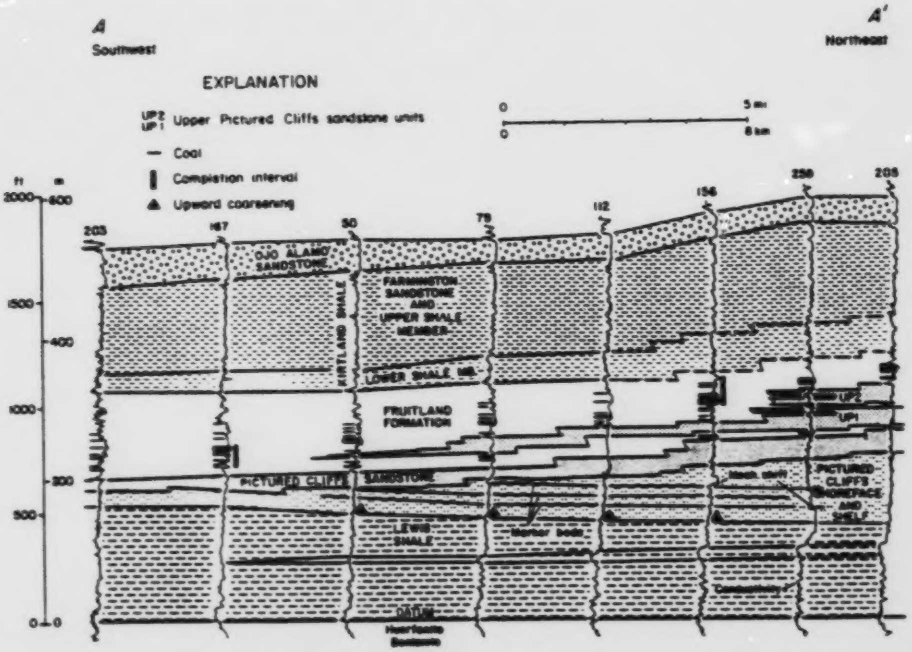
A
Southwest
A'
Northeast
EXPLANATION
UP2 UP1 Upper Pictured Cliffs sandstone units
Coal
Completion interval
Upward coarsening
0
5 mi
0
8 km
ft
m
2000
600
1500
400
1000
300
500
0
0
203
167
50
79
112
156
258
205
OJO ALAMO SANDSTONE
KIRTLAND SHALE
FARMINGTON SANDSTONE AND UPPER SHALE MEMBER
LOWER SHALE MB.
FRUITLAND FORMATION
PICTURED CLIFFS SANDSTONE
UP2
UP1
PICTURED CLIFFS SHOREFACE AND SHELF
Marker beds
LEWIS SHALE
DATUM
Huerfanito Bentonite

Figure 3. Stratigraphic cross section A-A'. The Fruitland Formation is a coal-bearing, coastal plain unit deposited landward (southwest) of the regressive Pictured Cliffs Sandstone that prograded into the Western Interior Seaway. See Figure 5 for location.

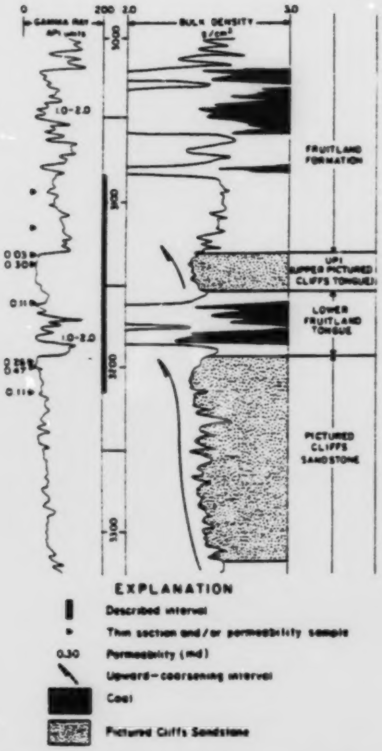

Figure 4. Gamma-density log of Blackwood and Nichols NEBU No. 403 well, located in Figures 1 and 5. Cored interval is described in Figure 7. Permeabilities are from core plugs in sandstones and well tests in coal beds.

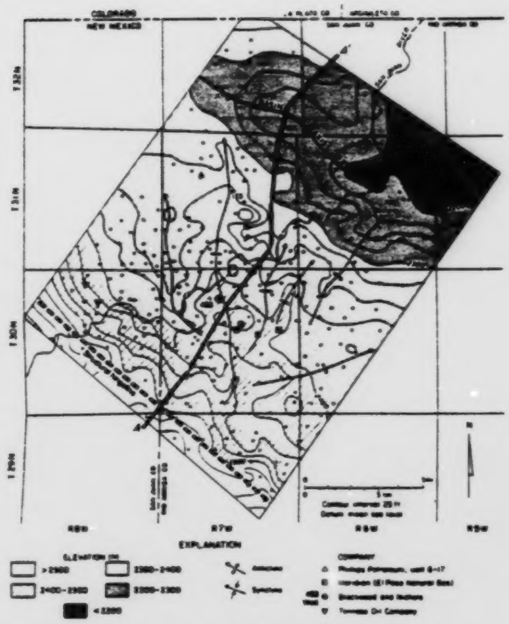
COLORADO
NEW MEXICO
T32N
T31N
T30N
T29N
R8W
R7W
R6W
R5W
EXPLANATION

Figure 5. Structure map of the Huerfanito Bentonite Bed showing location of cross section A-A; (Figure 3). A major synclinal axis crosses the northern quarter of the area, and the structural hingeline crosses the southwest part of the map. Minor folds may form conventional traps and contribute fracture permeability to Fruitland coal beds.

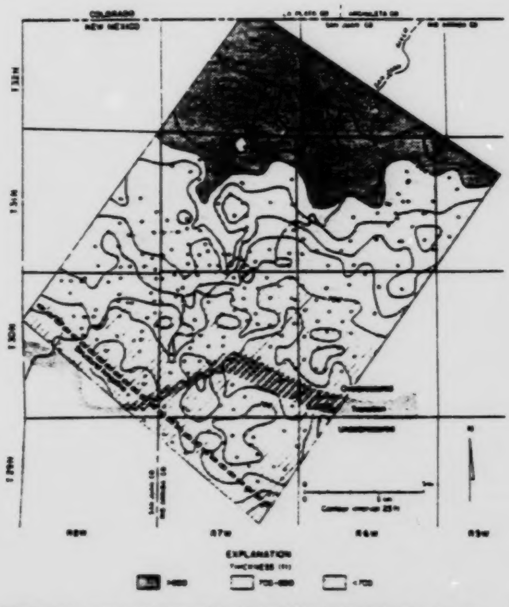
COLORADO
NEW MEXICO
T32N
T31N
T30N
T29N
R8W
R7W
R6W
R5W
EXPLANATION

Figure 6. Isopach from Huerfanito Bentonite Bed to top of Pictured Cliffs Sandstone (Figure 3). Generalized boundary between overpressured and underpressured Fruitland strata is from Kaiser, Swartz, and Hawkins (1991).

Two structure maps (Figures 1 and 5) of the Huerfanito Bentonite Bed, within the Lewis Shale (Figure 3), delineate a major synclinal axis that crosses the northeast quarter of the Navajo Lake area. South of this synclinal axis, an anticline, centered in T30N and T31N, R7W, has 22 to 30 m (75 to 100 ft) of structural relief and plunges northward toward the syncline (Figure 5). It is flanked on the west by a north-plunging syncline with similar amplitude, and on the east by a series of low-amplitude, northeast-plunging folds. Minor faults (displacements less than 15 m [50 ft] are documented in some well logs) are inferred in some areas where structural relief changes abruptly.

The northwest-trending structural hingeline of the basin (Ayers and others, 1991) crosses the southern part of the area (Figure 1). This hingeline is inferred to be a broad, northwest-trending complex of normal faults downthrown to the northeast. It occurs at the boundary between the northeast-dipping southern flank of the basin and the nearly flat-lying, but folded, basin floor. Where the hingeline projects to outcrop in La Plata coal mine at the western margin of the basin (Figure 1), there are three, northwest-trending normal faults having a net throw of approximately 70 m (230 ft). Moreover, in the area of the inferred hingeline, seismic reflection studies (Huffman and others, 1991) suggest northwest-striking basements faults that may extend into younger strata.

ISOPACHOUS TRENDS

The Huerfanito Bentonite-Pictured Cliffs Sandstone interval thickens from 205 m (675 ft) at the south to 260 m (850 ft) at the north end of the Navajo Lake area (Figure 6), consistent with a north or northeast paleoslope; basinward thickening of the interval averager 1.9 m/km (10 ft/mi). Slight thinning and thickening at the axes of the minor anticlines and synclines, respectively, suggest syndepositional tectonic activity. A minor increase in thickness along the structural hingeline (compare Figures 5 and 6) indicates possible syndepositional faulting.

SEDIMENTARY FACIES

Framework facies of a depositional system are composed of the coarsest grained sediment and are deposited by the highest energy processes operating within the system; they are the skeletal elements of the depositional system. In the Pictured Cliffs Sandstone, framework facies are barrier-strandplain, delta-front, and distributary/tidal channel-fill sandstones, and in the Fruitland Formation, framework facies are fluvial channel-fill sandstones deposited by ancient rivers carrying sediment to the Pictured Cliffs shoreline. Nonframework facies is a collective term applied to finer-grained sediments marginal to the framework facies and represents deposition by lower energy processes. Nonframework facies of Pictured Cliffs barrier-strandplain and deltaic systems are washover fan, tidal flat, lagoon, back-barrier marsh, and delta plain. Common nonframework facies in the Fruitland Formation are natural levee, floodplain, lacustrine, and swamp (coal) facies. To determine controls on coal occurrence, thickness, and trends, we mapped framework facies in the Fruitland Formation, the Pictured Cliffs Sandstone, and the upper Pictured Cliffs tongues.

PICTURED CLIFFS FRAMEWORK FACIES

Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone is the depositional platform upon which Fruitland peats (coals) accumulated, whereas upper Pictured Cliffs sandstones bound coal seams in the basinward (northeast) direction. In geophysical logs, the Pictured Cliffs Sandstone is divisible into upper and lower units. The lower unit is composed of a series of upward-coarsening sequences that are interpreted as upward-shoaling shelf and shoreface mudstone and sandstone interbeds (Figure 3). The upper unit of the Pictured Cliffs Sandstone has a blocky log signature and is interpreted to be a series of amalgamated barrier-strandplain and/or wave-dominated deltaic sandstones. This upper unit of the Pictured Cliffs contains well-sorted and crossbedded sandstone (Figures 4 and 7). Grain size increases slightly upward to medium-grained sand near the top of the unit, but the upper 0.5 to 1.2 m (2 to 4 ft) of the Pictured Cliffs consists of fine-grained sand. The fine-grained upper part of the unit contains planar and contorted laminae and abundant plant fragments; the interval is organically stained. In the Navajo Lake area, two Pictured Cliffs amalgamated sandstone units range from 12 to 36 m (40 to 120 ft) in thickness and strike northwestward (Ayers and Zellers, 1991).

Upper Pictured Cliffs Sandstones (UP1 AND UP2)

The basinward thickening of the interval between the Huerfanito Bentonite and the Pictured Cliffs Sandstone (Figure 6) results from shoreline progradation into a subsiding basin; note the basinward shift of the updip limits of successively younger marker beds (time lines) that originate in the shelf facies and terminate in the shoreline facies (Figure 3). Progradation of the Pictured Cliffs shoreline, dependent on complex interactions of sediment supply, variable rates of basin subsidence across the structural hingeline, and eustasy, was intermittent, resulting in shoreline stillstands. Periodically, shoreline movement reversed direction, and the Pictured Cliffs shoreline migrated southwestward over (transgressed) the Fruitland Formation, resulting in intertonguing of upper Pictured Cliffs sandstone beds with the Fruitland Formation. Two upper Pictured Cliffs tongues (UP1 and UP2) are present in the Navajo Lake area (Figure 3). Upper Pictured Cliffs tongues consist of crossbedded, burrowed, fine-grained sandstone that overlies a coal-bearing lower Fruitland tongue (Figures 3, 4, and 7). These sandstones grade upward into planar-bedded, medium-grained sandstones that make up the upper two-thirds of the Pictured Cliffs tongue (Figure 7). UP1 and UP2 sandstones trend northwestward and are as much as 30 m (100 ft) thick (Figures 8 and 9). They thin updip (southwestward), and their boundaries were placed where net sandstone thickness is 6 m (20 ft). The depocenter of UP1, defined by the 70-ft (21-m) contour in Figure 8, coincides with a depocenter of the underlying Pictured Cliffs Sandstone (Ayers and Zellers, 1991, their Figure 7), suggesting that increased rates of subsidence north of the structural hingeline created greater accommodation space, and hence, controlled shoreline position. Northeast-oriented fluvial or tidal channel-fill sandstones are inferred where the 60-ft contour projects landward (southwest) from areas of more than 27 m (90 ft) of UP1 sandstone (Figure 8). UP1 pinches out basinward, northeast of the study area. UP2 offlaps UP1 (its depocenter is basinward of UP1), reflecting net Pictured Cliffs regression (Figures 8 and 9).

FRUITLAND FORMATION FACIES

Framework Facies

The Fruitland Formation is a coastal plain unit deposited landward of the Pictured Cliffs shoreline (Figure 3). Framework facies of the Fruitland Formation were delineated in the net-sandstone map (Figure 10). The net thickness of Fruitland sandstone, which ranges from 9 to 30 m (30 to 100 ft), is lowest in the northern third of the area where the Fruitland Formation intertongues with the upper Pictured Cliffs sandstones (Figure 3). In the Navajo Lake area, individual Fruitland fluvial sandstones are less than 12 m (40 ft) thick and, most commonly, are 6 to 9 m (20 to 30 ft) thick. These elongate sandstone bodies trend northeastward (Figure 10), down the inferred paleoslope. Geophysical log signatures of Fruitland sandstones are upward-fining, spiky, and serrate, consistent with a fluvial channel-fill origin; northeast-flowing Fruitland rivers flanked Fruitland swamps and supplied sediment to the Pictured Cliffs shoreline. The thinness of Fruitland sandstones suggests that fluvial systems in the Navajo Lake

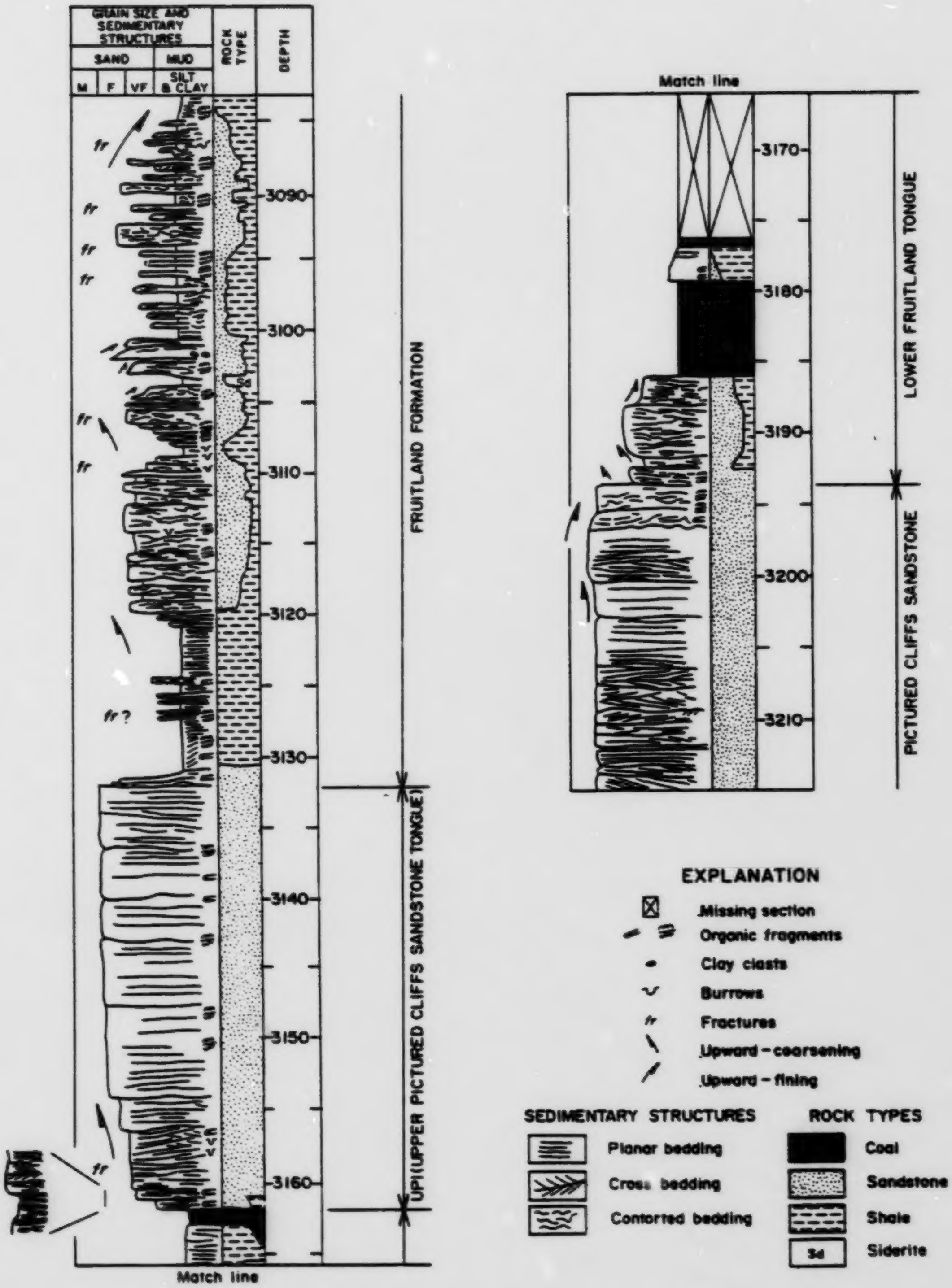
GRAIN SIZE AND SEDIMENTARY STRUCTURES
SAND
MUD
M
F
VF
SILT & CLAY
ROCK TYPE
DEPTH
fr
fr?
Sd
-3090-
-3100-
-3110-
-3120-
-3130-
-3140-
-3150-
-3160-
FRUITLAND FORMATION
UP1(UPPER PICTURED CLIFFS SANDSTONE TONGUE)
Match line
Match line
-3170-
-3180-
-3190-
-3200-
-3210-
LOWER FRUITLAND TONGUE
PICTURED CLIFFS SANDSTONE
EXPLANATION
Missing section
Organic fragments
Clay clasts
Burrows
Fractures
Upward-coarsening
Upward-fining
SEDIMENTARY STRUCTURES
Planar bedding
Cross bedding
Contorted bedding
ROCK TYPES
Coal
Sandstone
Shale
Siderite

Figure 7. Core description of Pictured Cliffs Sandstone, lower Fruitland tongue, upper Pictured Cliffs tongue (UP1), and Fruitland Formation in Blackwood and Nichols NEBU No. 403 well (see Figure 4).

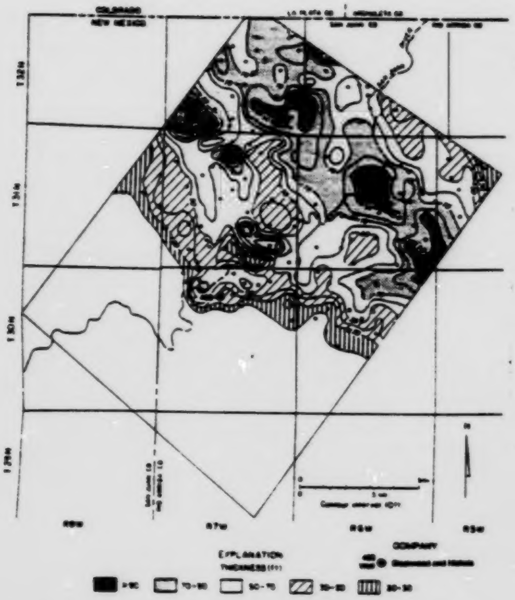
COLORADO
NEW MEXICO
LA PLATA CO
ARCHULETA CO
SAN JUAN CO
RIO ARRIBA CO
T 32 N
T 31 N
T 30 N
T 29 N
R8W
R7W
R6W
R5W
EXPLANATION
THICKNESS (FT)

Figure 8. Sandstone-isolith map of UP1 (Figures 3, 4, and 7). In the strike-elongate barrier-strandplain shoreline, landward (southwest) deflections of the 60-ft (18-m) contour may represent dip-elongate fluvial or tidal channel-fill sandstones. Area mapped is where net-sandstone thickness exceeds 6m (20 ft).

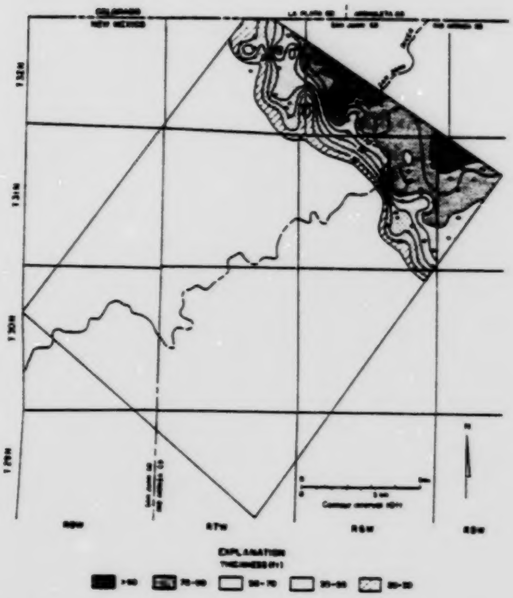
COLORADO
NEW MEXICO
LA PLATA CO
ARCHULETA CO
SAN JUAN CO
RIO ARRIBA CO
T 32 N
T 31 N
T 30 N
T 29 N
R8W
R7W
R6W
R5W
EXPLANATION
THICKNESS (FT)

Figure 9. Sandstone-isolith map of UP2 (Figure 3). Depocenter Of strike-elongate coastal sandstone is offset basinward of UP1 (Figure 8). Area mapped is where net-sandstone thickness exceeds (6 m) 20 ft.

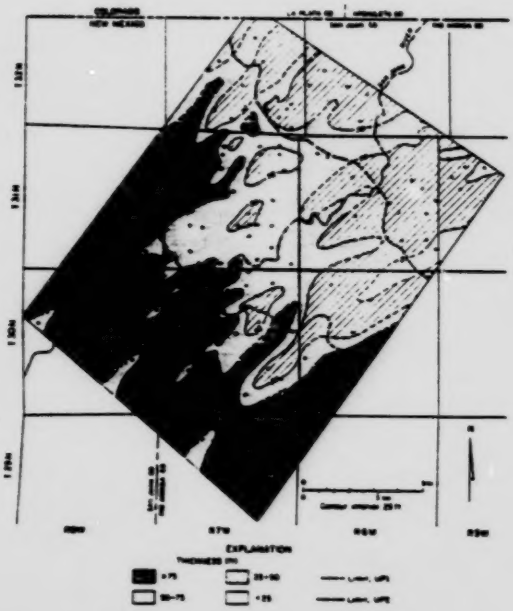
COLORADO
NEW MEXICO
LA PLATA CO
ARCHULETA CO
SAN JUAN CO
RIO ARRIBA CO
T 32 N
T 31 N
T 30 N
T 29 N
R8W
R7W
R6W
R5W
EXPLANATION
THICKNESS (FT)

Figure 10. Sandstone-isolith map of the Fruitland Formation. Net sandstone is greatest in the southwest part of the area. Dip-elongate sandstone bodies were deposited by Fruitland fluvial systems that supplied sediment to the Pictured Cliffs shoreline.

area were of insufficient size to form fluvially dominated deltas. This conclusion is supported by linear geometry of the Pictured Cliffs shoreline sandstone (for example, UP1; Figure 8), which suggests a wave-dominated coastline.

Nonframework Facies

Fruitland nonframework facies are coal beds, mudstones, and sandstones. Owing to their importance in this study, coal beds will be discussed separately in the following section. Nonframework sandstones typically are thin, ranging from a few inches to less than 4 m (15 ft) thick (Figure 7). These sandstones are fine-grained, rich in plant fragments, and commonly are interbedded with silty mudstone. They contain poorly preserved sedimentary structures that have been distorted by soft-sediment deformation, microfaults, and burrowing. Fruitland nonframework sandstones occur in upward-coarsening sequences 1 to 2 m (3 to 6 ft) thick and in amalgamated or upward-fining sequences as much as 4 m (15 ft) thick; these nonframework sandstones are interpreted to be crevasse splay and natural levee deposits.

FRUITLAND COAL

COAL OCCURRENCE, THICKNESS, AND TRENDS

Coal in the Fruitland Formation occurs in 2 to 14 beds that are most numerous in the southwest part of the Navajo Lake area and, in total, form a northwest-trending deposit (Figure 11). The greatest number of coal beds (Figure 11; 10 to 14 beds at the south) coincides with the location of greatest total coal thickness (greater than 27 m [90 ft]; Figure 12) and with the thickest individual bed (in the south, thicker than 9 m [30 ft]; Figure 13). In the Navajo Lake area, the net thickness of Fruitland coal beds ranges from 12 to 33 m (40 to 110 ft) (Figure 12). Net coal thickness is greatest, more than 21 m (70 ft), in the southwest, and is least in the northeast quarter of the area, which has 9 to 15 m (30 to 50 ft) of total coal. The northwest trend to net coal thickness, apparent here in the 50- and 70-ft (15 and 21-m) contours, is also present in regional coal maps (Fassett and Hinds, 1971; Kelso and others, 1987; Ayers and others, 1991).

A regional maximum-coal thickness map shows little internal complexity within northwest-trending belts of great maximum coal thickness (Ayers and others, 1991, their Figure 23), whereas the maximum coal map of the Navajo Lake area (Figure 13), which was made with closely spaced well control, suggests that geometry of individual coal seams in the northwest-trending belts is podlike or dip elongate. This map of the thickest Fruitland coal bed recorded in each well, regardless of its stratigraphic position, does not record thickness of an individual seam throughout the area. However, locally, as in the south corner of the map, an individual bed is mapped. Maximum coal thickness ranges from 4 to 15 m (15 to 50 ft) (Figure 13). Depocenters for thick coal, where individual coal beds are thicker than 9 m (30 ft), occur in pods 3 to 10 km (2 to 6 mi) across. Thick coal beds thin with distance from these depocenters, but they extend throughout most of the Navajo Lake area. A thick coal bed (thicker than 9 m [30 ft]; T29 and 30N, R7W) in the south coincides with an area of great net coal thickness (Figure 12) and indicates an area of persistent peat-forming conditions.

DEPOSITIONAL CONTROLS ON COAL OCCURRENCE,TRENDS, AND THICKNESS

The depositional setting of Fruitland coal seams in the Navajo Lake area was determined from coalbed trends and from relations between coal beds and Pictured Cliffs and Fruitland framework sandstones. Principal aspects of these relations are summarized in a map of depositional elements (Figure 14), in cross sections (Figures 15 and 16), and in the depositional

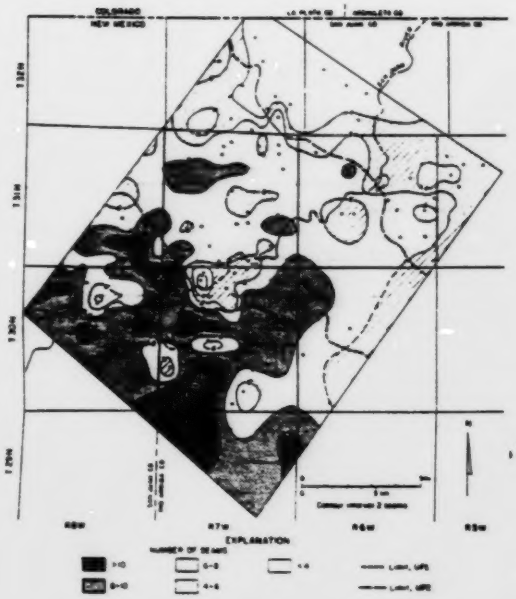
COLORADO
NEW MEXICO
T 32 N
T 31 N
T 30 N
T 29 N
R 8 W
R 7 W
R 6 W
R 5 W
EXPLANATION
NUMBER OF SEAMS

Figure 11. Fruitland coal-isopleth map. Fruitland Formation coal occurs in 2 to 14 seams that trend northwestward, parallel to upper Pictured Cliffs shoreline sandstones, UP1 and UP2 (Figures 8 and 9).

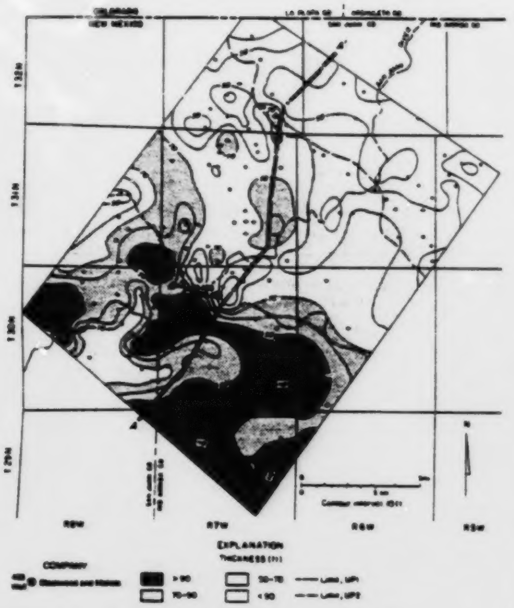
COLORADO
NEW MEXICO
T 32 N
T 31 N
T 30 N
T 29 N
R 8 W
R 7 W
R 6 W
R 5 W
EXPLANATION
THICKNESS (ft)

Figure 12. Fruitland coal-isolith map. Net-coal thickness ranges from 12 to 34 m (40 to 110 ft). Greatest net-coal thickness occurs in the southern third of the area, landward of and parallel to the northwest-trending upper Pictured Cliffs shoreline sandstones, UP1 and UP2 (Figures 8 and 9).

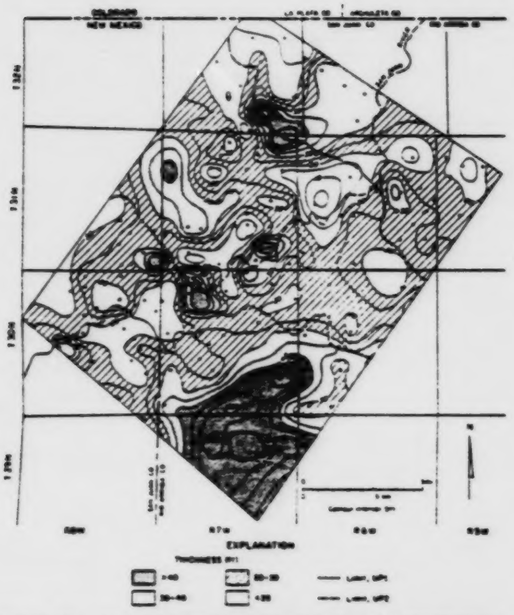
COLORADO
NEW MEXICO
T 32 N
T 31 N
T 30 N
T 29 N
R 8 W
R 7 W
R 6 W
R 5 W
EXPLANATION
THICKNESS (ft)

Figure 13. Fruitland maximum-coal map. Map of the thickest coal seam at each location shows a thickness range from 4.5 to 15 m (15 to 50 ft). Thickest coal is in the south, and no preferred orientation is apparent.

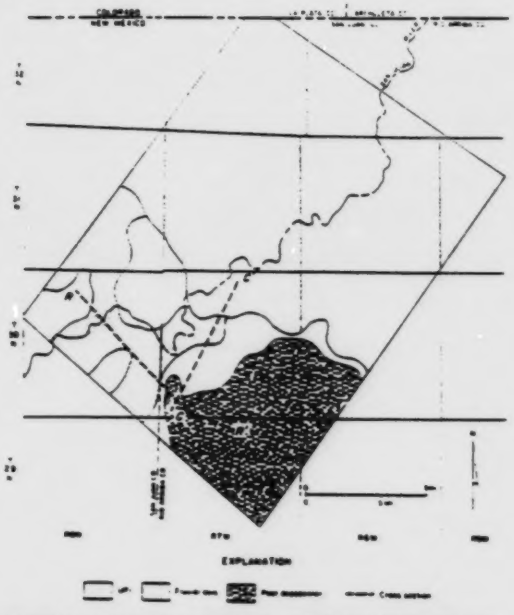
COLORADO
NEW MEXICO
EXPLANATION

Figure 14. Depositional elements of Fruitland Formation and upper Pictured Cliffs tongue, UP1, in the Navajo Lake area based on lateral relations seen in maps (Figures 8 through 13) and cross sections (Figures 15 and 16). Peat depocenter persisted southwest of the Pictured Cliffs shoreline and lateral to Fruitland fluvial depositional axes.

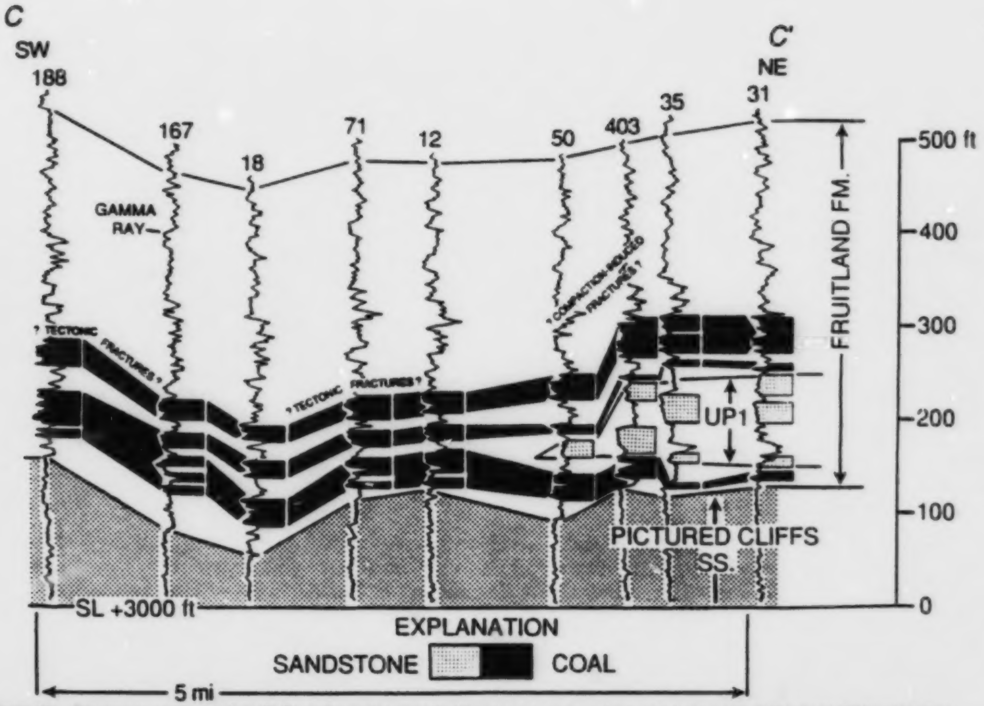
C
SW
C'
NE
188
167
18
71
12
50
403
35
31
GAMMA RAY
? TECTONIC FRACTURES ?
? TECTONIC FRACTURES ?
? COMPACTION-INDUCED FRACTURES ?
UP1
FRUITLAND FM.
PICTURED CLIFFS SS.
500 ft
400
300
200
100
0
SL +3000 ft
EXPLANATION
SANDSTONE
COAL
5 mi

Figure 15. Structural cross section C-C'. Although lower Fruitland coal seams pinch out landward of Pictured Cliffs shoreline sandstones, a thick upper Fruitland coal seam overrides UP1. Fractures may occur in areas of tectonic folding, such as between wells 188 and 71 in all seams, and in areas of compaction-induced folding where coal seams override shoreline sandstones, such as between wells 50 and 403 in the upper two thick seams. Well 188 ties with Figure 16. See Figure 14 for location.

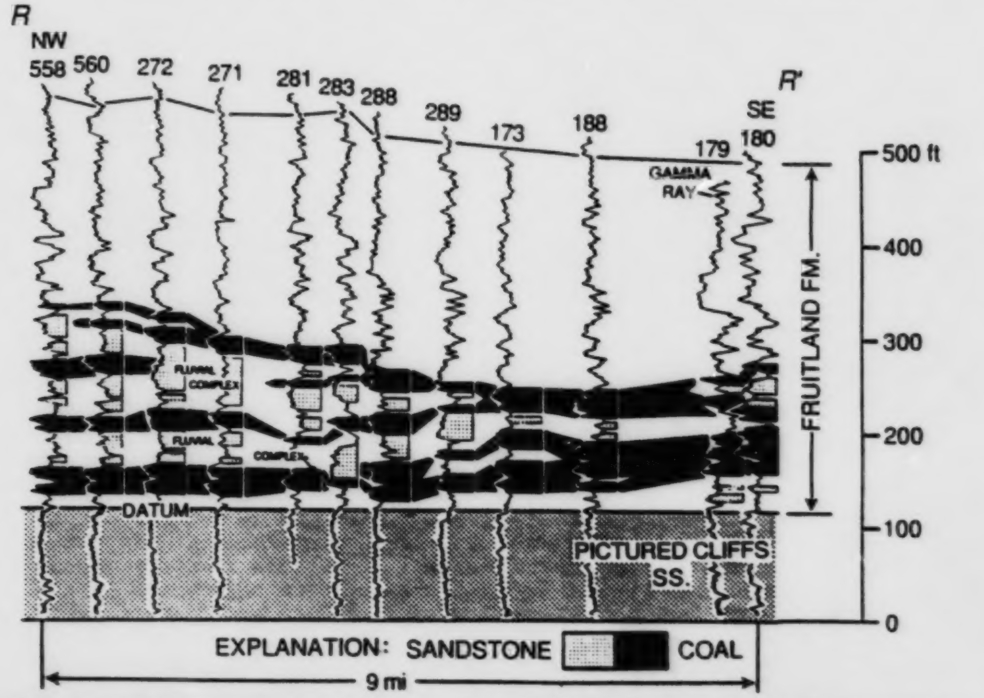
R
NW
R'
SE
558
560
272
271
281
283
288
289
173
188
179
180
GAMMA RAY
FLUVIAL COMPLEX
FLUVIAL COMPLEX
DATUM
FRUITLAND FM.
PICTURED CLIFFS SS.
500 ft
400
300
200
100
0
EXPLANATION: SANDSTONE
COAL
9 mi

Figure 16. Stratigraphic cross section R-R'. Thick Fruitland coal in well 188 forms zig-zag splits to the northwest where more compactable peat (coal) interfingers with fluvial complexes (sandstones) along paleostrike. Differential compaction may cause fracture-enhanced permeability. Because datum is the top of the Pictured Cliffs Sandstone, structural attitude of the coal beds is not shown. Well 188 ties with Figure 15. See Figure 14 for location.

model (Figure 17). In coal isopleth and isolith maps (Figures 11 and 12), strike-elongate trends are apparent, and coal seams are thickest and most abundant landward of upper Pictured Cliffs tongues. These relations suggest that thick peat formed in persistent, recurring swamps located landward of upper Pictured Cliffs shorelines. Although some coal beds terminate behind shoreline sandstones, other coal beds override them to form laterally extensive coal beds (Figure 16, upper two seams, and Figure 17). In the maximum coal map (Figure 13), coalbed geometry is podlike and dip elongate rather than strike elongate, owing to thick peat deposits that formed in peat depocenters between dip-elongate, Fruitland channel-fill sandstone complexes (Figures 14, 16, and 17). Northeast-aligned areas where maximum coal thickness is less than 6 m (20 ft) (as in the center of Figure 13) may reflect the presence of thin coal beds, where they interfinger with Fruitland fluvial complexes. Palynologic studies (Manfrino, 1984) and the low sulfur content of Fruitland coal indicate that peat accumulated in a fresh-water setting. Therefore, we conclude that the thickest peats formed inland, behind abandoned and foundering shoreline deposits of the Pictured Cliffs Sandstone (Figure 17).

STRUCTURAL CONTROLS ON DEPOSITIONAL SYSTEMS

We suggest that structural activity contributed to Pictured Cliffs shoreline stillstands in the Navajo Lake area and, indirectly, to the distribution of thick Fruitland coal seams (Figure 17). The Pictured Cliffs shoreline prograded rapidly across the southern half of the basin. After the shoreline crossed the structural hingeline, sporadic structural activity caused the northern part of the basin to subside more rapidly, allowing this area to accommodate a greater thickness of sediment. The changing balance between sediment input and pulsatory subsidence north of the hingeline resulted in oscillation and aggradation of the shoreline and allowed time for thick peat deposits to form landward of the aggrading shoreline. Fruitland net coal thickness is greatest landward of the upper Pictured Cliffs sandstones, UP1 and UP2.

RESERVOIR CHARACTERISTICS AND PRODUCTION

RESERVOIR CHARACTERISTICS

Fruitland coal beds occur at depths of 915 to 1 067 m (3 000 to 3 500 ft) at Navajo Lake. Coal rank is high-volatile B bituminous at the south and increases northward to medium-volatile bituminous, consistent with structural position and burial depth at Navajo lake (Scott and others, 1991). Ash content of Fruitland coal commonly is 15 to 30 percent. Gas content ranges between 14.8 and 20.3 cc/gm (475 and 650 SCF/ton) on a dry, ash-free basis, and gas in place is estimated to range between 142 and 424 MMm^3 (5 and 15 Bcf) per well, whereas recoverable gas is estimated to range between 71 and 212 MMm^3 (2.5 and 7.5 Bcf) per well, based on 130-hectare (320-acre) spacing and 50 percent recovery.

In most of the Navajo Lake area, Fruitland coal beds are characterized by bottom-hole pressures greater than 8 274 kPa (1 200 psi) and overpressure. Simple pressure gradient is greater than 9.80 kPa/m (0.43 psi/ft). Overpressuring is artesian in origin (Kaiser, Swartz, and Hawkins, 1991). Fruitland coal beds, the most permeable units in the Fruitland-Pictured Cliffs aquifer (Figure 4), receive recharge primarily at outcrop along the wet, elevated, northern margin of the basin in the Hogback Monocline (Figure 1). Ground-water flow is down the steep northern flank of the basin and across the nearly flat basin floor to a postulated no-flow boundary along the structural hingeline (Figure 1), where it turns vertically upward (Kaiser, Swartz, and Hawkins, 1991). At this point, the Fruitland potentiometric surface markedly steepens across the transition from overpressured to underpressured conditions (Figure 6). The transitional boundary between overpressured and underpressured conditions most likely is caused by (1) offset of aquifer coal beds across faults at the structural hingeline (Figures 1, 5 and 6), (2) southwestward pinch-out of coal beds, or (3) both. Coal beds in the Navajo Lake area may be either gas- or water-saturated. Fruitland coalbed gas is dry ($C_1/C_{1-5} > 95$ percent), and it contains a high percentage of carbon dioxide (commonly 3 to 10 percent) at Navajo Lake (Scott and others, 1991). Primary fractures (face cleats) in oriented cores from Blackwood and Nichols NEBU No. 403 well trend northeastward, consistent with regional cleat trends in the southern part of the basin (Tremain and others, 1991). In other parts of the Navajo Lake area, two strongly developed face cleat trends may be present (Tremain and others, 1991) and may contribute to high gas production rates through higher permeability. Highly productive wells in the Navajo Lake area are reported to have fracture-enhanced permeability that may or may not be predictable from lineament analysis. A recent study showed no significant relations between methane production and lineament attributes in the northern San Juan Basin (Baumgardner, 1991).

PRODUCTION HISTORY

The Navajo Lake area has produced coalbed methane for nearly 40 years. The Phillips No. 6-17 well (Figures 5) is often referred to as the discovery well for coalbed methane in the San Juan Basin. This well, which is an open-hole completion in upper Fruitland coal beds and sandstones, is located on the northwest flank of a minor, north-plunging anticline. It has produced for more than 35 years with little decline in gas production (averaging 4.5 to 5.1 Mm^3/d [160 to 180 Mcf/d]) or reservoir pressure (Hale and Firth, 1988). The well produces little or no water, indicating some element of structural and/or stratigraphic trapping; upper Fruitland coal beds in this well may not be connected to water-productive lower Fruitland coal beds to the south. Since 1985, many operators, including Meridian Oil, Phillips Petroleum, and Blackwood and Nickols, have completed coalbed methane wells in the Navajo Lake area. These wells, which are the most productive coalbed methane wells in the United States, commonly produce at rates of 8.5 to 425 Mm^{3}d (300 to 15 000 Mcf/d).

PRODUCTION TRENDS

To evaluate gas and water production from Fruitland coal beds, initial production data through 1991 were compiled from Rocky Mountain Coalbed Methane Reports (Petroleum Information Corp.). Because gas and water production from Fruitland coal beds are log-normally distributed (Kaiser, Ayers and others, 1991), production values were posted in log units and were contoured to delineate production trends. Reporting methods and reliability of data differ among operators, introducing uncertainty as to the quality of the data base; for example, many water-productive wells had no water production reported. In addition, we did not map production by completion method (fracture stimulation vs. cavitation). Recent studies have suggested that a cavitation completion may result in significantly greater production than a fracture stimulation (M. Mavor, personal communication, 1991). However, this improved production with open-hole cavity completions may apply only to wells located in geologic and hydrologic settings that favor high production rates regardless of completion type; in areas of low production at Navajo Lake, spot checks of completion type showed little production difference between wells completed by the two methods.

Despite the above limitations, regional gas and water production trends are mappable (Figures 18 and 19). Initial gas production ranges from less than 2.8 Mm^3/d (100 mcf/d) to more than 622 Mm^3/d (22 000 Mcf/d) (Figure 18). A strongly developed primary northwest trend is enclosed by both the $10^{2.5}$- and $10^{3.0}$-contours (316- and 1 000-Mcf/d or 8.9- and 28-Mm^3/d contours). Within the northwest-trending belt of highly productive wells, the $10^{3.5}$-contour (3 160 Mcf/d or 89 Mm^3/d) delineates secondary northeast-

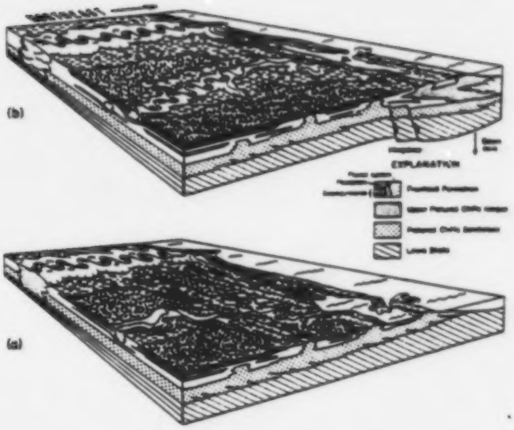

Figure 17. Depositional model of Fruitland coal beds in the Navajo Lake area. (a). Peat is deposited behind, and overrides, abandoned and foundered Pictured Cliffs shoreline sandstones. Area is crossed only by minor fluvial systems that shift periodically. (b) Intermittent subsidence north of structural hingeline causes shoreline stillstand and allows accumulation of thick, extensive peat deposits. Not to scale. Modified from Ayers and Zellers (1988).

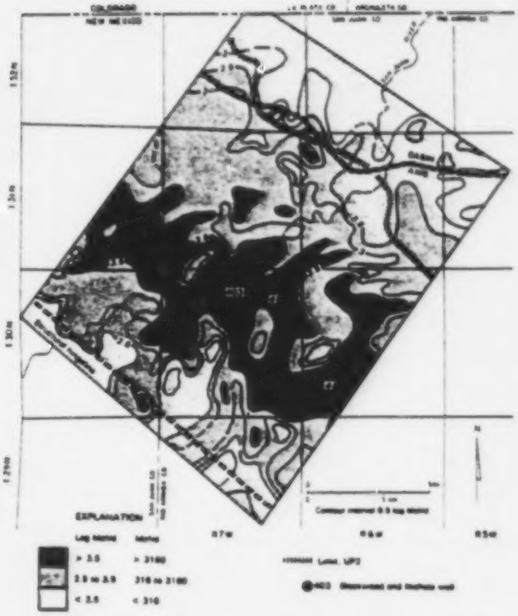

Figure 18. Map of initial gas potential from Fruitland coalbed wells, Navajo Lake area. Wells producing more than 8.9 Mm3 (316 Mcf/d) occur in a broad, northwest-trending belt; a secondary, northeast-trending pattern of highly productive wells may reflect anomalously thick coal or fracture trends.

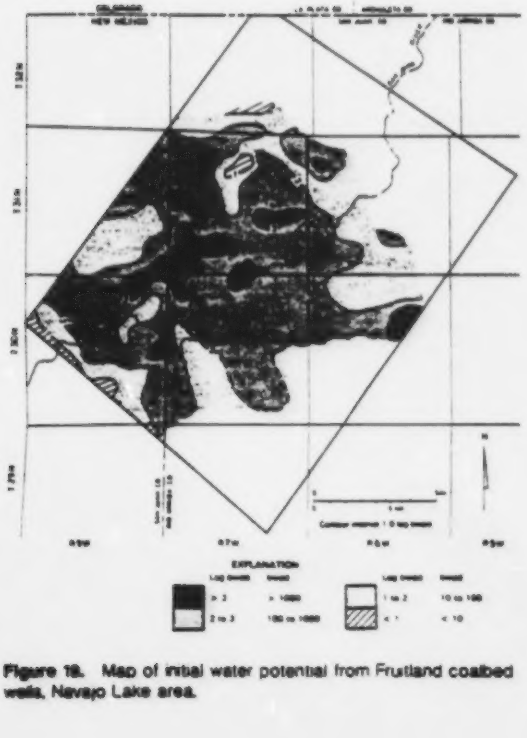

Figure 19. Map of initial water potential from Fruitland coalbed wells, Navajo Lake area.

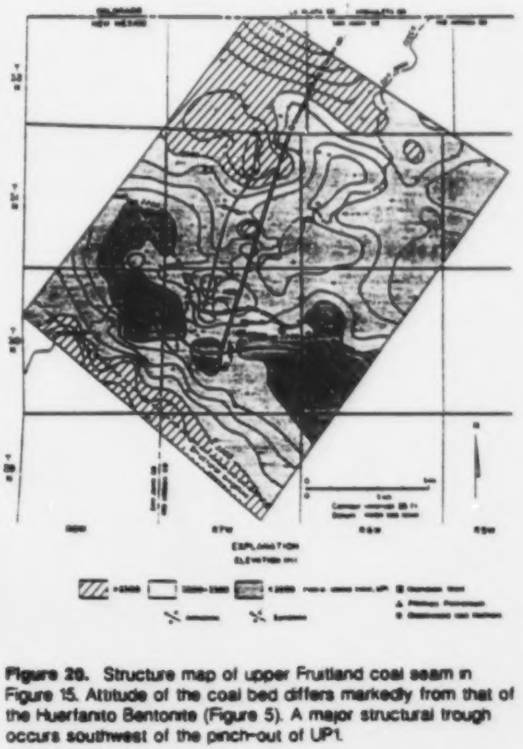

Figure 20. Structure map of upper Fruitland coal seam in Figure 15. Attitude of the coal bed differs markedly from that of the Huerfanito Bentonite (Figure 5). A major structural trough occurs southwest of the pinch-out of UP1.

trending patterns of highest initial gas production. Patterns of initial water production, like those in the initial gas production map, trend primarily northwestward and secondarily northeastward (Figure 19), but these patterns are poorly defined, partly because much less water production data was available.

DISCUSSION OF CONTROLS ON METHANE OCCURRENCE AND PRODUCIBILITY

Occurrence and producibility of coalbed methane in the Navajo Lake area result from a combination of geologic and hydrologic factors. The distribution of thick coal beds (reservoirs) is controlled by depositional setting, which in turn was structurally controlled; tectonically induced subsidence north of the hingeline temporarily confined the Pictured Cliffs shoreline to a narrow belt, and this stillstand allowed thick peat to accumulate on the aggrading Fruitland coastal plain.

Some Fruitland coal beds may be regionally continuous, overriding or underlying upper Pictured Cliffs tongues and Fruitland channel-fill sandstones (Figures 15 and 16). Although these coal beds pinch and swell and commonly form zig-zag splits similar to those described in coal-bearing strata in other basins (Britten and others, 1975; Ayers and Kaiser, 1984), many beds are laterally continuous, which contributes to development of a regional aquifer system. Moreover, where Fruitland coal beds drape over or under sandstones, they may have a higher fracture density and, hence, greater permeability (Figure 15). The structural attitude of an upper Fruitland coal bed (Figure 20) differs markedly from the structural attitude of other strata, such as the Huerfanito Bentonite (Figure 5).

Our maps and cross sections show that the complex nature of Fruitland coal beds (Figures 15, 16, and 17) has threefold significance. First, coalbed methane reservoirs are extensive. Second, compaction-induced fractures, and therefore enhanced coalbed permeability, may occur in areas where laterally extensive coal beds drape over shoreline sandstones or form zig-zag splits with channel-fill sandstone complexes. Finally, the great lateral extent of coal beds is critical to the interpretation of ground-water flow and overpressure in the Fruitland Formation in the northern San Juan Basin (Kaiser, Swartz, and Hawkins, 1991).

In the gas production map (Figure 18), the primary northwest-trending pattern of high production, delineated by the $10^{2.5}$- and $10^{3.0}$-contours (316- and 1 000-Mcf/d or 8.9- and 28-Mm^3/d contours), coincides with the greatest net coal thickness (Figure 12) and lies landward of the upper Pictured Cliffs tongues. It also coincides with high bottom-hole pressures and regional overpressure (Kaiser, Swartz, and Hawkins, 1991). Moreover, along the southwest margin of the northwest-trending belt of high initial gas production, the $10^{2.5}$- and $10^{3.0}$-contours (316-and 1 000-Mcf/d or 8.9- and 28-Mm^3/d contours) are closely spaced (Figure 18), suggesting that the artesian-overpressured coalbed reservoirs in the highly productive trend are, for the most part, hydrologically disconnected from the underpressured coal beds to the southwest, owing to (1) offset of the beds along northwest trending faults associated with the structural hingeline, (2) southwestward pinch out thick coal beds, or (3) both. Free gas and dissolved gas as well as adsorbed gas are inferred to exist in overpressured Fruitland coal beds. Within the northwest-trending belt of highly productive wells, the secondary northeast trends, delineated by the $10^{3.5}$- and $10^{4.0}$-contours (3 160-Mcf/d and 10 000-Mcf/d or 89-Mm^3/d and 283-Mm^3/d contours), may represent enhanced permeability associated with systematic fractures (face cleats) due to tectonic activity or compaction-related folding flanking Fruitland channel-sandstone complexes. Northeast trends of high initial gas production (Figure 18) correspond to net-sandstone thicks (Figure 10).

The northeast boundary of the area of high initial gas production ($10^{2.5}$-contour [316-Mcf/d or 8.9-Mm^3/d], Figure 18) coincides with the northeast boundary of high net-coal thickness and the updip limit of UP2 (Figure 12, 50-ft [15-m] net-coal thickness contour). Thus, lower production rates to the north may reflect thinner reservoir rock and/or lower permeability. However, this boundary also coincides with the synclinal axis of the basin (Figures 1 and 5), and alternatively, free gas may have escaped up the southwest flank of the Ignacio Anticline (Figure 1).

CONCLUSIONS

1. During Late Cretaceous time, the Pictured Cliffs shoreline prograded northeastward into the Western Interior Seaway. Sporadic tectonic activity caused increased subsidence rates northeast of a northwest-trending structural hingeline, which in turn, increased accommodation space and caused major shoreline stillstands and deposition of upper Pictured Cliffs tongues, UP1 and UP2. These upper Pictured Cliffs tongues interfinger with the continental Fruitland Formation to the southwest.

2. Stillstands of the Pictured Cliffs shoreline allowed aggradation of the Fruitland coastal plain deposits, including thick peat beds. Strike-elongate trends in coal-occurrence maps indicate that peat formed behind the northwest-trending upper Pictured Cliffs shoreline sandstones. Although thin lower Fruitland coal beds pinch out behind these upper Pictured Cliffs tongues, thick coal beds commonly override abandoned shoreline sandstones. Individual coal beds are podlike or dip-elongate rather than strike-elongate, because along paleostrike, they interfinger with, or thin and override, northeast-trending Fruitland fluvial channel-fill sandstone complexes.

3. Coalbed methane productivity trends reflect the depositional and structural fabrics and the hydrodynamics of the Fruitland Formation.

4. The most productive coalbed methane wells at Navajo Lake occur in a 15-km (10-mi) wide, northwest-trending belt that (1) coincides with net coal thickness greater than 15 m (50 ft), (2) is regionally overpressured, and (3) is bounded on the south by the structural hingeline and on the north by a major synclinal axis.

5. Both adsorbed and free gas are present in Fruitland coal beds in the Navajo Lake area. Coalbed methane may be hydrodynamically trapped at a no-flow boundary where thick coal beds pinch out to the southwest and where they are offset along the structural hingeline; the most productive wells in the basin are less than 8 km (5 mi) northeast of this structural hingeline.

6. Minor structures that may cause conventional trapping and fracture-enhanced permeability are common at Navajo Lake. Individual Fruitland coal beds must be mapped to identify minor structures; owing to differential compaction, structures mapped on individual coal beds or on regional marker beds will vary markedly.

ACKNOWLEDGMENTS

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QUAD NEUTRON LOGS AND COAL BED METHANE

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The general use of geophysical drill-hole logs for the coal industry commenced in the late 1960's with the use of slim line oilfield logging tools. These tools and the existing log interpretation techniques were inadequate for the quantitative evaluation of coal deposits. In the 1970's, with the availability of miniaturized electronics, Research and Development programs undertaken by small logging companies resulted in advanced tools and evaluation methods.

The development of the Coal-Water-Ash (CWA) model provided, for the first time, a stand alone, quantitative log method for the determination of in situ coal reserves. This method is a truly independent method, in that it is not dependent upon empirical correlation(s) to physical samples. Good agreement was obtained between the CWA log method and the traditional physical samples (cores etc.) method, providing the physical samples were subjected to a TWO-LABORATORY procedure which involved the use of both Oilfield and Coal laboratories. To obtain realistic in situ coal reserves for a given deposit, the proportions of coal seam components (including wet ash, porosity, porosity fluids [gas and/or liquid], coal matter etc.) must be taken into account.

QUAD NEUTRON log measurements, developed by Roke Oil Enterprises Ltd., employ balanced configuration techniques in order to eliminate or minimize the adverse drill-hole effects. Consequently, satisfactory log measurements can be obtained in open-holes and drill-holes containing tubular goods.

The Quad Neutron Prorosity, Quad Neutron Clay and the Quad Neutron Liquid, along with other log measurements, are customarily displayed on the Neutron Formation Composite (NFC) log. The NFC log is currently being used for the detection of in situ absorbed Coal Bed Methane. The discussion will address log presentation, the use of Quad Neutron measurements for the Quantification of the absorbed Coal Bed Methane and log response to other in situ coal parameters.

NOTES

UTILIZATION ALTERNATIVES FOR COALBED METHANE FRON THE SYDNEY COALFIELD IN NOVA SCOTIA

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ABSTRACT

The longwall operations of the Cape Breton Development Corporation mine the deep submarine coal seams of the Sydney coalfield. They currently release to the atmosphere about 200 000 cubic meters of methane per day, from two collieries less than 1km apart. This is equivalent in heating value to 100 000 tons of coal per year, about 3% of the coal being mined.

At Lingan Colliery, 50% of its methane is recovered at about 50% purity. It is extracted from holes drilled upward into the collapsing strata after the longwall shearer has removed the coal. The holes are connected by a piping system to vacuum pumps in a methane drainage plant on the surface. The balance is released underground from both current operations and mined out areas. It is diluted to safe levels by the ventilation air. By the time it reaches the surface, this mine return air can contain up to 1% methane.

A number of studies by engineering consultants have examined ways to utilize this wasted resource, and attain environmental benefits. One study examined use of the 50% methane stream for cogeneration, using internal combustion engines and a hot water space heating system. Others showed that the heating value of the 1% methane in air mixture can be recovered by using it as combustion air for a 600MW coal fired power plant less than 3km from the collieries.

None of the projects have been implemented. The impending closure of Lingan will eliminate the 50% methane source. The retreating longwall technique used in Phalen Colliery may allow long-term mining to proceed without a methane drainage system. However methane drainage may be feasible if the economics become favorable.

INTRODUCTION

The Sydney Coalfield is on the southern edge of a large submarine sedimentary deposit that extends about 200km to the south coast of Newfoundland (Figure 1). The outcrop extends for

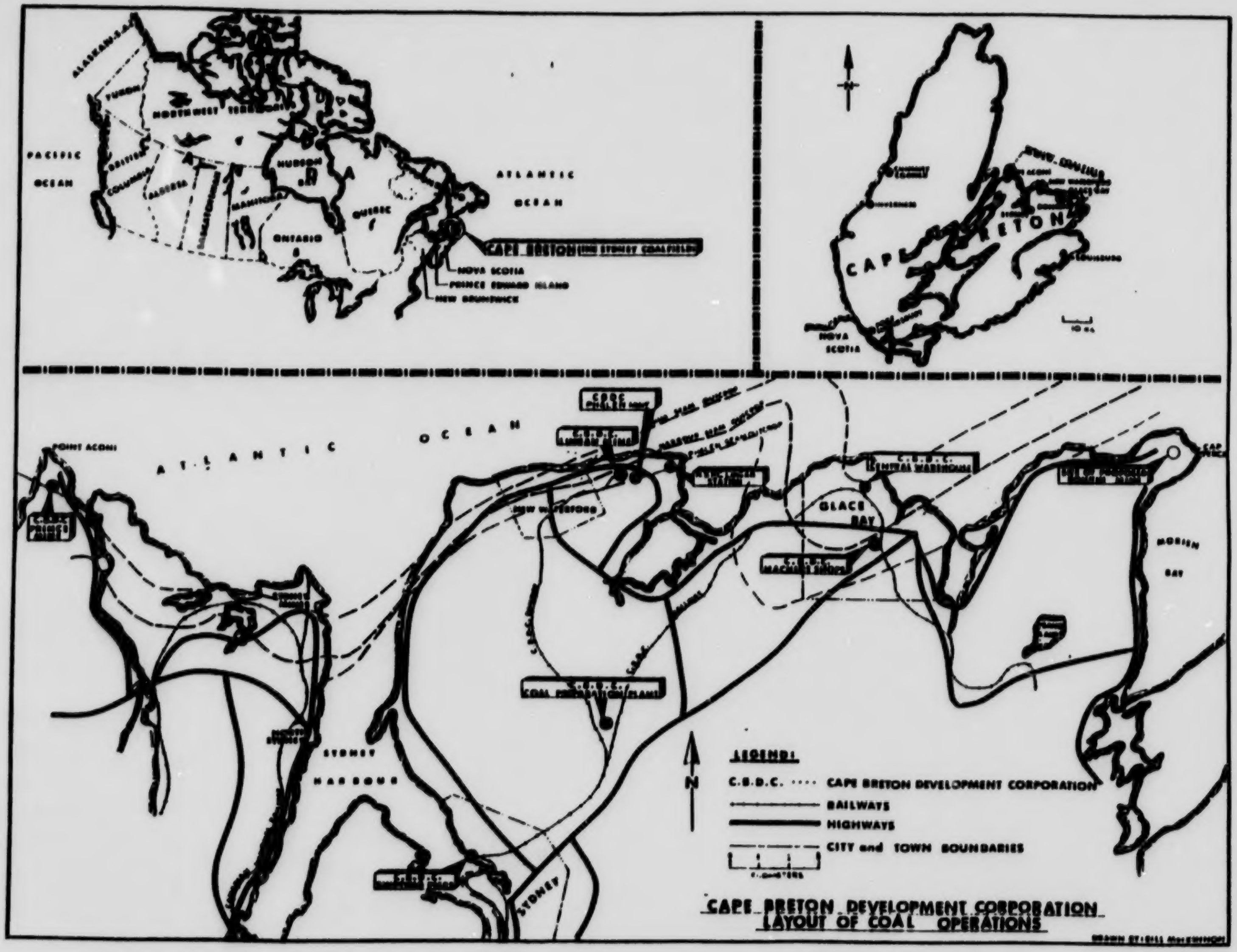
PACIFIC OCEAN
ALASKA
YUKON
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
HUDSON
ONTARIO
QUEBEC
ATLANTIC OCEAN
CAPE BRETON (THE SYDNEY COALFIELD)
NOVA SCOTIA
PRINCE EDWARD ISLAND
NEW BRUNSWICK
CAPE BRETON
NOVA SCOTIA
10 mi.
N
ATLANTIC OCEAN
POINT ACONI
C.B.D.C. PRINCE MINE
CBDC PHALEN MINE
C.B.D.C. LINGAN MINE
C.B.D.C. CENTRAL WAREHOUSE
GLACE BAY
C.B.D.C. MACHINE SHOPS
NEW WATERFORD
C.B.D.C. COAL PREPARATION PLANT
SYDNEY HARBOUR
NORTH SYDNEY
SYDNEY
MORIEN BAY
CAP
LEGEND:
C.B.D.C. .... CAPE BRETON DEVELOPMENT CORPORATION
RAILWAYS
HIGHWAYS
CITY and TOWN BOUNDARIES
KILOMETRES
CAPE BRETON DEVELOPMENT CORPORATION
LAYOUT OF COAL OPERATIONS

Figure 1. Layout of Cape Breton Development Corporation coal operations

about 50km along the north-east coast of Cape Breton Island. There are 11 mineable seams in the Sydney Coalfield sequence. Measured plus indicated reserves are 1.2 billion tons. Inferred reserves are an additional 1.2 billion tons. Reserve limitations are within 8km of land and less than 1200 meters of cover.

Most of the reserves are high volatile "A" bituminous. Rank increases from west to east and with increasing depth. Offshore drilling has determined that reserves of some seams near the maximum 1200 meter depth are medium volatile in rank.

Seams dip gently seaward at about 5 degrees except near the outcrop where the dip is up to 15 degrees. There are gentle folds but dip rarely exceeds 15 degrees. There are no faults across the field. Thicknesses range from 0.9 to 4 meters.

Coal is characterized by a medium to high sulphur content, mostly in the form of finely disseminated pyrite. Most of the seams have medium to low ash content.

MINING HISTORY

Coal has been mined on Cape Breton since 1720 and to date the Sydney Coalfield has yielded about 350 million tons. Almost all the mineable coal that was not submarine has been recovered. Initial mining was from the most accessible outcrops in many small mines. In the early 1900's most of the mining operations were consolidated in a large mining company and the collieries enlarged and mechanization slowly began. By the 1960's the operation had become uneconomic, and the owners announced in 1967 that the collieries were to be abandoned. The Federal Government, threatened with the major sociological impact of such an event formed the Cape Breton Development Corporation (CBDC).

All of the collieries that existed in 1967 have been closed. Three collieries are operating at present: Prince, Lingan and Phalen. They are all submarine with seam thicknesses from 2 to 2.5 meters. Output this fiscal year is expected to be about 4.4 million tons.

Mining is exclusively by longwall with Prince and Phalen using the retreat method. Lingan has employed advancing longwall to date but its next (and likely last) face will be retreating. Lingan is slated to close in early 1993 when its last developed longwall panel is exhausted. The reason for closure is high production costs.

Present employment is about 2700. This will reduce to less than 2000 with the closure of Lingan.

All collieries use slopes following the seam to access the operations underground. Coal clearing is exclusively by conveyors from the face to storage/railcar-loading silos on the surface. Primary ventilation is by surface mounted exhaust fans, with secondary ventilation by auxiliary fans underground.

The Corporation is fully integrated, operating its own railway, preparation plant, shipping pier and repair shops. Both metallurgical and thermal coal are produced by washing Phalen and Lingan coal together in a three-product, heavy-medium cyclone prep plant. Prince coal is not washed. About half the output is sold to the Nova Scotia Power Corporation (NSPC) and the balance mostly to overseas customers.

IMPACTS OF METHANE

Management of methane is one of the major costs of the CBDC mining operations. The higher rank coals of Lingan and Phalen collieries release substantial methane as they are cut from the face. The disturbance of the overlying (and to a lesser extent, underlying) seams and strata as the roof collapses behind the longwall contributes much more methane. Present methane content, in situ, is 7 to 9 cubic meters per ton.

Ventilation air is directed to all active areas to dilute and remove methane. Monitors measure methane levels at key positions and shut down power supplies if methane exceeds 1.25%.

On the advancing faces of Lingan colliery, and in previous collieries as well, it has been necessary to collect some of the methane as a relatively high purity stream to reduce ventilation air requirements on the wall face and improve safety. This methane drainage technique is described more fully in the next section.

When coal is cut from the face by the shearer, methane is released by a combination of desorption from the internal surfaces of the coal and diffusion to the outside of the particles.

The rate of release is described by an exponential decay, (Airey equation) with a "half life" dependent on particle size and coal type. The largest particles of prepared coal, about 25mm, take about 600 hours to lose half of their methane content. Smaller particles desorb much faster.

METHANE DRAINAGE SYSTEM IN LINGAN COLLIERY

From the top level and immediately behind the longwall face holes are drilled up into the strata at about a 60 degree angle from the horizontal, to a depth of 40 meters. The lower 10 meters is 75mm case pipe which is grouted to prevent air infiltration. The balance is open hole (Figure 2). Holes are normally spaced at 20 to 30 meter intervals as the face advances.

Each drainage hole is connected by a flexible hose to a 200mm collection main which is extended as the wall moves forward. The collection main runs to a 300mm trunk line which in turn runs to 350mm and 400mm pipe lines extending up the slope to the surface and the methane extraction plant.

The extraction plant houses five Nash model CL2002 vacuum pumps driven by 200hp motors. They maintain a negative pressure of about 50kPa at the pump inlet and draw methane from the various drainage holes underground. In normal operation only 3 pumps are operated.

Overall gas purity is about 55% methane. This level is maintained by periodic measurement of the methane content of the individual drainage holes and adjustment of the valve to control extraction rate. A vacuum of only 1kPa is necessary to induce the required removal rate at the flow regulator valve. Flow in excess of gas make will draw air up into the fracture zone and dilute the gas. Available gas is at a maximum just behind the face. About 10 holes are kept active behind the face. Once flow and purity drop below predetermined levels the hole is shut off.

In Lingan a longwall panel is up to 2400 meters long with a face of 213 meters. When a panel has been completely mined and all salvageable equipment removed, the top and bottom levels are sealed. A 200mm pipe is installed through the top level seal and connected through a valve to the 300mm trunk line. Over time, after sealing, the methane content increases and adds to the total methane output. It also helps to reduce the inevitable leakage of methane from the sealed walls into the main ventilation stream.

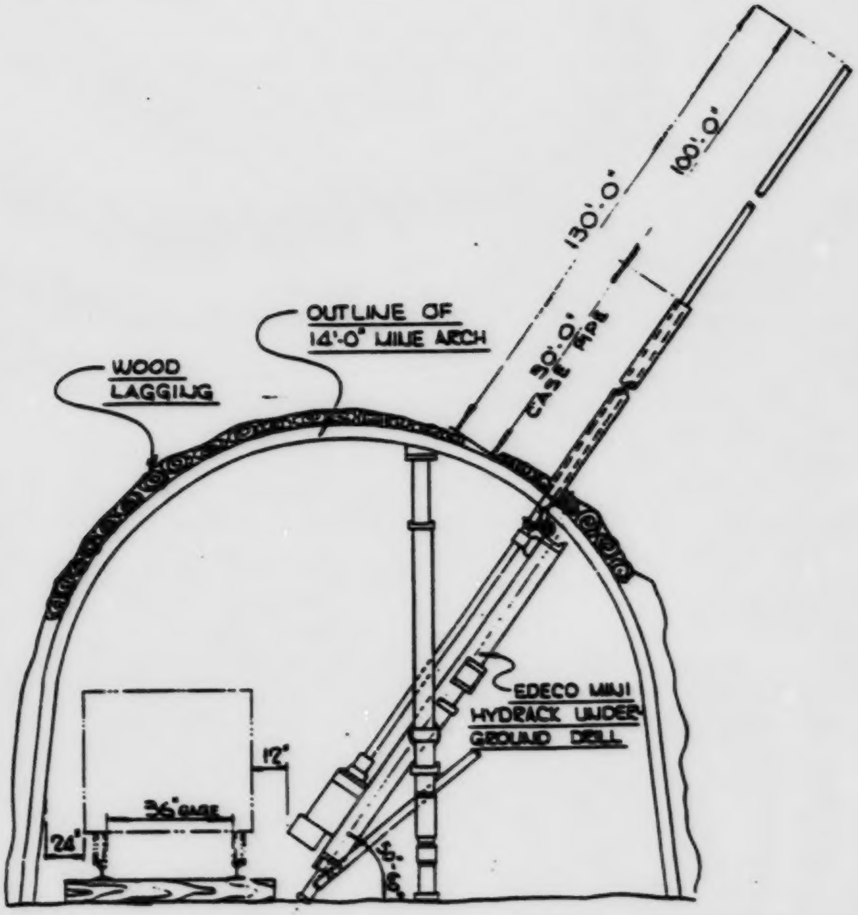

Figure 2. Drilling arrangement for methane drainage

Gas flow from the methane drainage system at Lingan is about 1.4 cubic meters per second at 55% purity. Total gas flow and quality vary within a very narrow range in day-to-day operation.

PHALEN PLANS

At present there is no methane drainage system in Phalen. The retreat mining system there includes a bleeder deep at the far end of the longwall panels which runs roughly parallel to the main deeps. The top level of each wall is connected to the bleeder. As the longwall retreats toward the main deeps, methane is released in the way already described. By regulation of ventilation flows, a small fraction of the air that comes up the wall is directed toward the bleeder. This sweeps all the methane released from the strata away from the main ventilation stream and the working areas. The balance of the ventilation air goes out the top level.

At the time of writing, careful consideration is being given to a consultant's recommendation, based on favorable UK experience, that would alter the system by elimination of the bleeder deep as such, but allow the worked out walls to provide a path for methane flow to a single collecting point (Figure 3).

Bleeder flow will be regulated by a single valve at the top of the bleeder level. In addition, flow into the bleeder system on the operating wall will be controlled by careful regulation of the ventilating air pressure. In this way, methane released into the collapsed area behind the face will flow through the bleeder system.

Methane purity is expected to be in the range of 25% because there will be some air flow into the collapsed area so that the air/methane interface is kept well back from the faceline. This system is expected to operate without the need for a methane drainage system.

As new walls are developed they will be connected to the bottom end of the previous wall.

To obtain a supply of higher purity methane it will be necessary to install a methane drainage system in Phalen similar to that described for Lingan.

COLLIERY VENTILATION

Both collieries are ventilated by large suction fans located on the surface. A summary of ventilation and drainage flows is shown in TABLE 1.

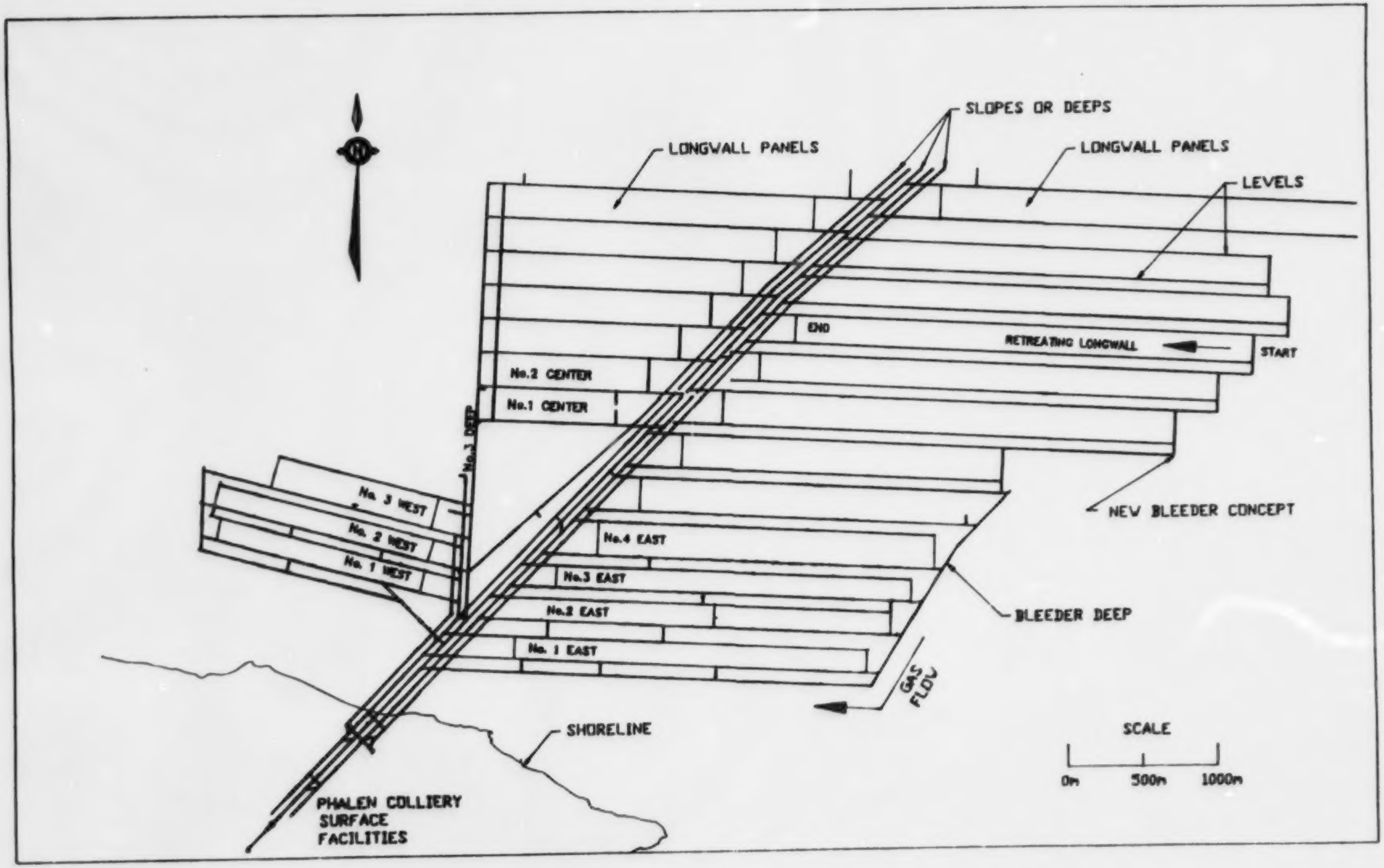
SLOPES OR DEEPS
LONGWALL PANELS
LONGWALL PANELS
LEVELS
END
RETREATING LONGWALL
START
No.2 CENTER
No.1 CENTER
No.1 DEEP
No. 3 WEST
No. 2 WEST
No. 1 WEST
NEW BLEEDER CONCEPT
No.4 EAST
No.3 EAST
No.2 EAST
No. 1 EAST
BLEEDER DEEP
GAS FLOW
SHORELINE
SCALE
0m
500m
1000m
PHALEN COLLIERY SURFACE FACILITIES

Figure 3. Phalen Colliery Layout

TABLE 1 Ventilation and Drainage Flows and Qualities

Stream	Present		Future	
	Flow rate (m^3/s)	Methane (%)	Flow rate (m^3/s)	Methane (%)
Lingan				
Ventilation	165	0.4	165	0.4
Drainage	1.4	55	1	55
Phalen				
Ventilation	170	0.6	170	0.4
Drainage			1	50
or Bleeder			2	25

MINE METHANE UTILIZATION

PRELIMINARY INVESTIGATION (1983 STUDY)

By 1981 Lingan Colliery was the major CBDC producer with output of 1 200 000 tons per year. As the mined-out area enlarged and production increased, ventilation air requirements approached $200m^3/s$ at a methane content of about 0.8%. This contained methane, over a year, has the equivalent heating value of about 70 000 tons of coal or approximately $0.4*10^{12}$ kcal.

In the previous year NSPC had commissioned the second 150MW coal fired unit in a station that was planned to reach 600MW. It was located within 2.5km of Lingan Colliery.

Some preliminary investigations revealed that:

1) Lingan Colliery ventilation airflow roughly matched the combustion air requirements of two 150MW units at full load.
2) Air containing methane at levels well below the lower explosive limit of 5% can be safely raised to the boiler air preheater temperature of 300C without preignition.
3) Methane is a fuel source with zero ash and sulphur.
4) Air with 0.8% methane has 8% of the fuel needed for stoichiometric combustion.

Based on these facts CBDC solicited engineering proposals for a preliminary study of the design and cost of a system to transport the mine return air (MRA) to the Lingan Generating Station and introduce it into the boilers.

The final report recommended an insulated, corrugated, prefabricated duct 3.6m in diameter. It was to be above ground with a length of 2800m. Flow was to be by use of an induced draft fan powered by a 900hp motor located at the generating station. A number of safety features were included to safeguard the operation of the colliery and the power plant.

The only problem identified was an appreciable loss of MRA to the stack gases by leakage in the air preheaters. The project, based on the fuel and capital costs of the day, appeared to have a favorable rate of return. However, NSPC, which had cooperated fully during the study, concluded that it was not prudent to proceed at that time. NSPC's reasons were: 1) the concept was new and untried and had not been demonstrated elsewhere; 2) Lingan Station was the newest and soon to be largest of the NSPC system so there was reluctance to introduce complications to the operation; 3) there were perceived hazards in introducing methane in any form to a coal fired plant.

Consequently the project was shelved.

MINE DRAINAGE METHANE (MDM) UTILIZATION (1987 STUDY)

By 1986 the methane extraction plant at Lingan was running and venting to the atmosphere an average of $0.7m^3/s$ of methane.

CBDC commissioned a study to determine the feasibility and cost of utilizing this stream as a fuel to produce electric power. Gas turbines were considered but, based on UK experience, a bank of 5 modified reciprocating gas engines was recommended, with a total output of 6.5MW. A heat recovery system was also included, sufficient to supply 90% of the needs of both Lingan and the adjacent new Phalen Colliery. A circulating hot water system was designed to provide space heating, water heating for showers and preheating of mine ventilation air during the winter months, replacing both oil fired and electric systems.

Power generated was to supply the needs of both collieries with excess going for sale to the NSPC grid.

The financial return on the project, while positive, was not enough to meet the requirements of CBDC which was struggling to reduce operating costs and to remain within a capital budget needed to sustain mining operations.

The project did not proceed.

MINE METHANE UTILIZATION 1991 STUDY

The utilization of mine methane at the Lingan Generating station was the subject of a more detailed reexamination, prompted by a number of new or changed factors:

1) The possible use of MDM as a reburn fuel to reduce NO_x.

2) Recognition of the impact of methane discharged to the atmosphere as one of the major contributors to the greenhouse effect.

3) The additional supply of methane in the MRA of Phalen Colliery, opened late in 1984, which increased mine methane supply to a coal equivalent of 100,000 tons per year.

4) Increased emphasis on reduction of SO_x and NO_x emissions.

Study basis

The study evaluated costs and benefits without assigning any value to the methane. It was understood that if the project was financially attractive then the two parties to any agreement to proceed, NSPC and CBDC, would negotiate a business arrangement, establishing a price for the methane, and allocating capital an operating costs.

Project benefits

The estimated benefits of substituting methane for about 100,000 tons of coal at the Lingan Generating Station were:

1) Reduction of SO_2 emissions by 5400 tons per year since the mine methane is sulphur free.

2) Reduction of NO_x emissions by 600 tons per year due to the absence of any fuel-bound nitrogen.

3) Reduction of CO_2 emissions by about 100,000 tons per year due to the lower carbon/hydrogen ratio of methane when compared to coal.

Much more difficult to quantify is the reduction in the total greenhouse effect. While there is considerable debate in the scientific community on the magnitude, it is recognized that the methane molecule absorbs and reflects infrared energy at a much greater rate than the carbon dioxide molecule. The ratio of the effects also varies depending on the time horizon over which the effects are integrated. This ratio is highest in the first 25 years. No quantification of the reduction in total greenhouse effect was agreed upon. There was, however, recognition that the project being considered was probably the most cost effective way that dilute methane-in-air mixtures could be disposed of.

Concepts examined

The possibility of extracting or concentrating the methane in MRA was examined but quickly dismissed as being prohibitively expensive.

The benefits of using the MDM as a "reburn" fuel were examined. In this relatively new technology used to reduce NO_x generation, a portion of the boiler fuel is introduced into the upper part of the boiler. By use of MDM as the injectant some of the NO_x produced by the primary flame is reduced to N_2.

To investigate this option, pilot scale tests were done by CANMET in the combustion test unit at the Bell's Corners Labs. The tests used CBDC coal and natural gas to simulate Lingan boiler conditions. The technique was effective in reducing NO_x. However, because the available MDM is sufficient for only 8% of the fuel required by one 150MW boiler at full load, insufficient to fully realize the benefits of reburning, it was determined that there were other, more cost effective ways to attain the same NO_x reduction.

The cost of this option is substantial because of the 200mm pipeline from the gas extraction plant to the generating station. Other costs were the capital and operating cost of the compressor needed to attain the 300kPa required at the burners, plus boiler modifications to introduce a secondary fuel.

Chosen option

In the configuration chosen, all methane is delivered as a dilute methane-in-air mixture. The MDM from the Lingan gas plant is mixed with the MRA at Lingan Colliery. Two 4m diameter feeder ducts carry the MRA from both collieries to a point near the Phalen fan. The Lingan branch is 950m long, the Phalen branch only 100m. There the duct enlarges to 4.8m and runs 1600m to the Lingan Generating Station (Figure 4).

At the collieries the ducts are directly connected to the ventilating fan discharges. Each is fitted with a rapid acting emergency damper which deflects flow of MRA directly to atmosphere should excessive levels of methane be detected or other emergencies arise.

The Lingan MDM presently discharges to atmosphere from the gas plant within 100 meters of the fan discharge. In the chosen option the MDM discharge is piped into the MRA line and mixed with it by use of a diffuser, carefully designed to avoid all possible risk as the methane concentration passes through the combustible range. This raises the methane content from 0.4 to 0.8%. A series of methane sensors and controls prevent excessive methane levels from developing. A minimum MRA flow rate is set to keep duct velocity well above the flame propagation rate as a further safeguard.

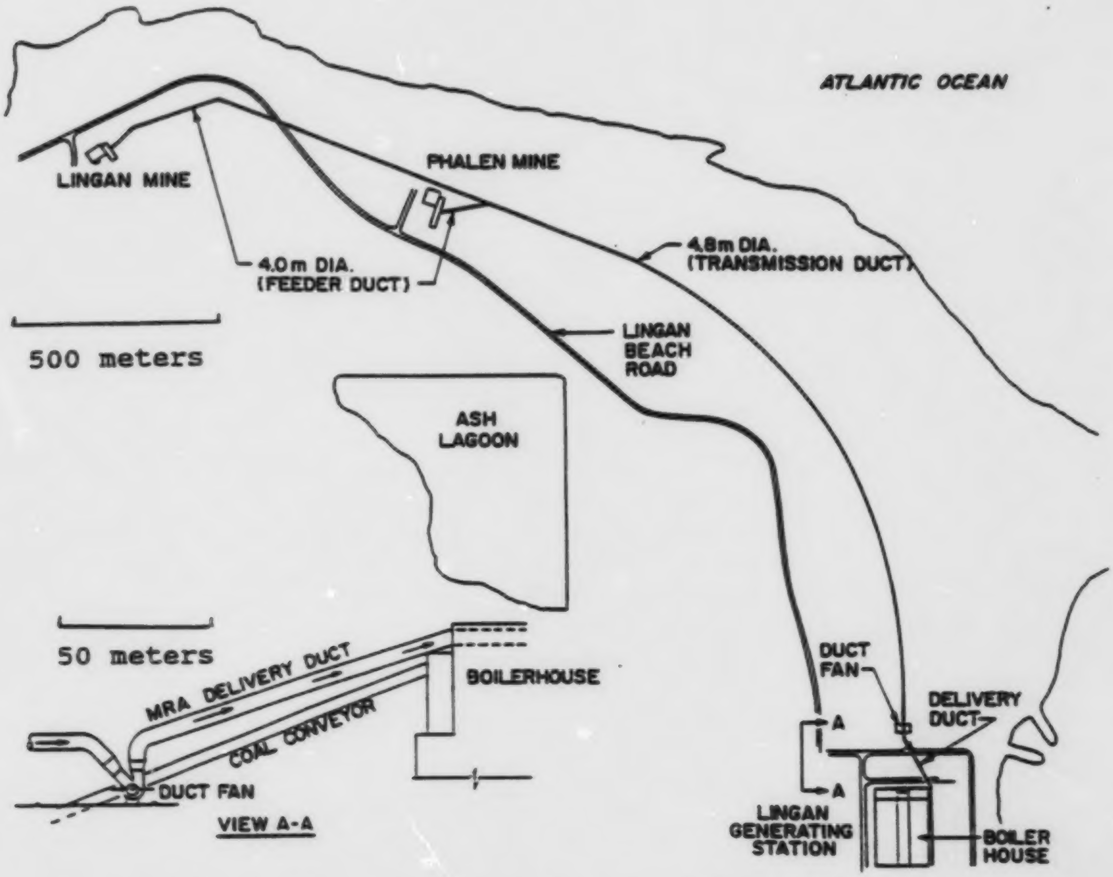
ATLANTIC OCEAN
LINGAN MINE
PHALEN MINE
4.0m DIA.
(FEEDER DUCT)
4.8m DIA.
(TRANSMISSION DUCT)
500 meters
LINGAN BEACH ROAD
ASH LAGOON
50 meters
MRA DELIVERY DUCT
COAL CONVEYOR
BOILERHOUSE
DUCT FAN
VIEW A-A
DUCT FAN
A
DELIVERY DUCT
A
LINGAN GENERATING STATION
BOILER HOUSE

Figure 4. Mine methane duct general layout

Controls are arranged so that both the power plant and the collieries can easily revert to the present mode of operation at any time without upsetting the each other's operation.

Transmission duct design

The recommended option for duct construction is a helical corrugated steel pipe (CSP). The diameter chosen requires that the pipe be fabricated on site, a practical approach because of the quantity involved. A smooth inner liner is included to reduce friction loss. An external insulation is sprayed on to reduce heat loss and prevent condensation during the cooler months. The pipe is elevated on steel supports. CSP manufacturers contacted were not aware of any precedents for ducts of this diameter and length. Right-of-way is not expected to be a problem since, with the exception of one small lot, all the land to be crossed is owned by either NSPC or CBDC. There is no residential or commercial use of the area. However, it is recognized that a duct of this diameter is highly visible. Fortunately the terrain is such that most of the 4.8m section is hidden from the highway.

Because the duct carries air, with about 1% methane and at a pressure slightly below atmospheric, it is not classified as a gas pipeline and is therefore not subject to the regulations which govern gas pipeline construction and operation.

A variable inlet vane induced-draft fan with a 1700kW motor is located at the power plant. Fan discharge is carried to the top of the boiler house by an inclined duct. A 4.4m square duct is attached to the outside of the building. It carries the MRA to the forced draft fan intakes for each boiler. (Figure 5). An interface plenum is mounted over the fan inlet. Dampers on one side prevent methane laden air from entering the boiler room and on the other side control the influx of MRA.

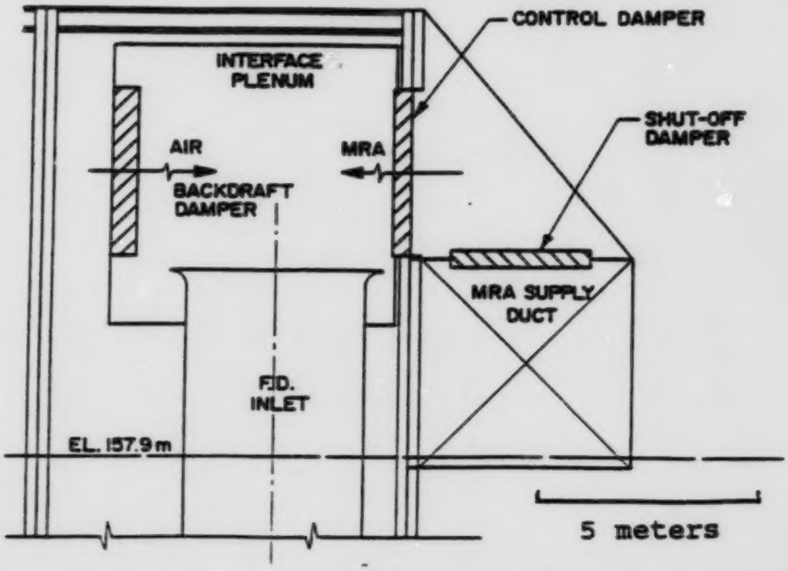

Figure 5. Boiler isolation and control dampers

Coal grinding mill safety

Each boiler is equipped with two Ljungstrom rotating type combustion air heaters. As pointed out earlier MRA can be preheated safely and without preignition. However the Lingan Station design uses part of this preheated air as primary air (PA) to dry and convey coal ground in the coal mills. In normal operation the mills process a very fuel rich mixture of air and coal. During startup and shutdown the fuel mixture passes through a stoichiometric range. Recent studies (Amyotte, 1991) on CBDC coals have confirmed an increased hazard if methane is a component of such mixtures.

To minimize the risk it is necessary to provide new PA fans and supply them with methane-free air from the interior of the boiler house. To preheat this air the Ljungstrom heaters would be extensively modified to a trisector design (Figure 6). Other modifications to the air heaters would reduce MRA leakage to the flue gas and PA streams. The reworking of in-plant equipment is very costly, adding about 50% to the overall cost of the project. Additionally, boiler outage time is needed to do the work.

Present status

Overall cost is estimated to be in the $50 million range, which cannot be economically justified by the value of the identified benefits. For this and other reasons the project has been shelved.

Soon after the study was completed, in early 1991, CBDC discontinued development work at Lingan Colliery. In July it was announced that Lingan will close in early 1993. This will reduce substantially but not eliminate an MRA stream from Lingan. The abandoned workings must be kept pumped of water and ventilated because of Phalen Colliery 135m below.

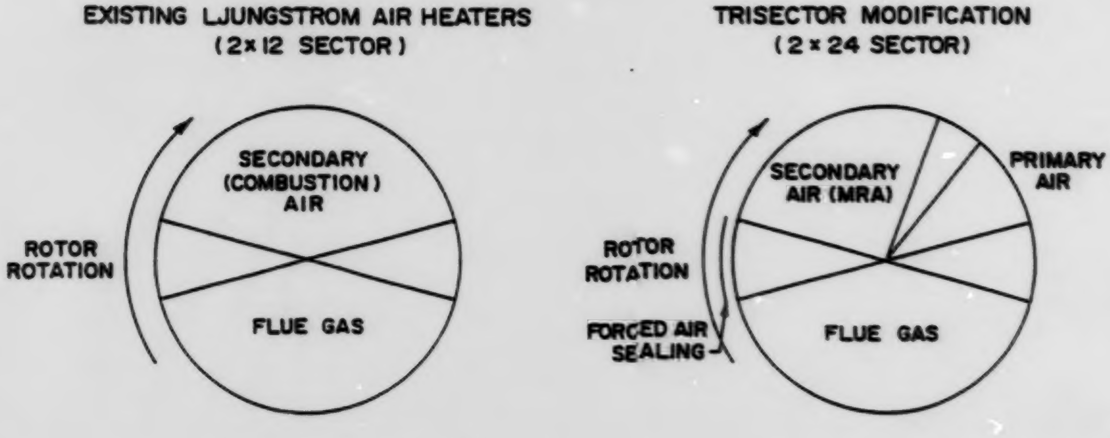
EXISTING LJUNGSTROM AIR HEATERS
(2×12 SECTOR)
SECONDARY
(COMBUSTION)
AIR
ROTOR
ROTATION
FLUE GAS
TRISECTOR MODIFICATION
(2×24 SECTOR)
SECONDARY
AIR (MRA)
PRIMARY
AIR
ROTOR
ROTATION
FORCED AIR
SEALING
FLUE GAS

Figure 6. Ljungstrom air heater modifications

CURRENT WORK

Recently a private group obtained approval from NSPC and CBDC to proceed with a project to install a gas turbine at the minesite to produce electric power from mine methane. Final decisions will depend on many of the factors outlined above. The feasibility of drilling in-seam in Lingan Colliery for extraction of additional methane is also being examined.

OTHER INVESTIGATIONS

The combustion of very lean mixtures has been examined by many investigators. For example (Weinberg 1974) found that a device constructed in much the same way as a spiral heat exchanger could be used to combust a mixture of less than 2% methane in air. Combustion is along the axis of the unit with the products of combustion leaving through one channel, heating the incoming fuel mix in the other channel. Work at MIT (Peterson, 1985) has examined the possibility of combining a device similar to the Ljungstrom air heater with a gas turbine. By extracting some of the heat from the combustion of a 2% methane mix to preheat the incoming fuel mix stable combustion can be attained. The gas turbine is then used to extract additional energy from the hot gases.

No commercial applications of these concepts have been made to our knowledge.

A recent study for the US EPA (Energy Systems Associates) surveyed US coal mines for sites where utilization of ventilation air may be possible. Their criteria were 1) within 8km of a suitable boiler 2) methane emissions greater than 6000m^3 per day and over 0.25% methane. Six sites were identified. Only one was closer than 3km. The greatest methane release was 70 000m^3 per day.

CONCLUSIONS

These studies have given both the producer and potential consumer of mine ventilation air a clear understanding of the benefits and costs of utilization. Should economic or environmental circumstances change this work will provide a solid base for reevaluation.

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NOTES

ECONOMICS OF COAL BED METHANE PROJECTS IN THE WESTERN CANADIAN BASIN

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INTRODUCTION

The potential for economic development of the coalbed methane resource in the Western Canadian Sedimentary Basin ("WCSB") is very intriguing in light of the phenomenal growth of coalbed methane development in various areas in the United States.

The development of coalbed methane in the San Juan Basin of Colorado and the Black Warrior Basin in Alabama in the last several years has been remarkable. These developments were largely the result of the Unconventional Fuel Tax Credit provisions which provided the economic incentive; however, development in certain areas within each of the basins has been found to be economic, even without the benefit of the credit.

The provinces of Alberta and British Columbia do not have a similar unconventional fuel tax credit in place to spur the development of the coalbed methane resource. The Province of Alberta has in place an Alberta Royalty Tax Credit, which reduces the actual royalty payment for small producers. This credit does not have the same economic impact as the U.S. Unconventional Fuel Tax Credit.

The intent of this paper is: to review the potential for coalbed methane development in the WCSB in the context of the current and projected supply/demand situation for conventional gas; to project when the coalbed methane resource will be required to meet domestic and export demand; and, to compare the economic basis for coalbed methane development in the San Juan Basin with a similar, hypothetical development in the WCSB. The hypothetical cases for both the San Juan Basin and the WCSB were considered to be follow-up development opportunities after all land costs and exploration costs have been incurred.

SUPPLY/DEMAND MODEL

The WCSB is Canada's most significant source of natural gas and will supply Canadian domestic and U.S. export gas requirements well into the future from conventional sources of natural gas produced from existing, discovered inventories and from future reserves additions. These future reserves will be added as a result of continuing exploration within the Basin. The opportunity for future development of Canada's coalbed methane resources in the WCSB will be primarily a function of the ability of the conventional resource base to meet the anticipated increase in natural gas demand placed on the WCSB. Moreover, expansion of the existing pipeline transmission network serving the Canadian and U.S. markets will require continued development of additional supplies of both conventional and unconventional natural gas resources in the future, in order to maintain throughput in those systems.

In order to forecast the future Canadian supply/demand picture, it is first necessary to forecast the supply capability of the conventional resource base in the WCSB. Sproule Associates Limited ("Sproule") has developed a gas supply capability model which is designed to predict the future natural gas supply capability of the WCSB from conventional natural gas resources under stipulated market conditions of price and demand. The key forecasts generated by the Sproule model are the forecasts of productive capacity from the discovered gas reserves currently recognized as connected or unconnected and from the gas reserves to be added in the future as the result of exploration and development in the WCSB.

The point in time when the total productive capacity of the WCSB from conventional sources can no longer meet the anticipated demand levels will represent the opportunity for either unconventional or frontier sources of gas to be developed to supplement production from conventional WCSB gas resources. Unless the economic environment changes significantly with respect to either natural gas prices or government royalty and tax regimes, significant development of coalbed methane resources will be deferred until conventional supplies from the WCSB come into balance with demand.

The primary focus of the Sproule model is to investigate the magnitude and timing of the conventional reserves additions that could be expected to occur in the WCSB from continued exploration and development activities. The future supply of natural gas will be significantly affected by both price and demand. In the Sproule model, both price and demand are treated as input variables. The maximum sustainable productive capacity which the Sproule model identifies is by definition, "the maximum sustainable productivity capacity in a specific price and market environment".

The Sproule gas supply capability model is a statistically based model based on historical data obtained from the Canadian Petroleum Association Statistical Handbook.

The forecasts that Sproule prepared for this paper include price and demand scenarios which reflect current industry and government perceptions. The Sproule gas supply capability model is not an equilibrium model as both price and demand are treated as exogoneous variables by the model. Therefore, some judgement must be applied in the interpretation of the results presented by this paper as the predictions are specific to particular demand and price assumptions. However, because the main purpose of this paper is to discuss the potential for coalbed methane develoment, the results of the Sproule model will present a reasonable timeframe in which this development could be expected to occur given the current perceptions of future natural gas prices and demand.

The Sproule model forecasts are driven by two key mathematical equations: a reserves additions equation which relates cumulative reserves additions as a function of cumulative gas-intent drilling activity; and a drilling activity equation which relates annual gas-intent drilling as a function of five independent variables identified as net natural gas revenues, surplus productive capacity, drilling costs, annual natural gas sales, and the maturity level of the WCSB. The equations were developed based upon regression analysis techniques applied to the available historical data.

An important characteristic of the reserves additions equation is its ability to determine an inferred ultimate potential for conventional natural gas resources in the WCSB. The inferred ultimate potential of approximately 300 TCF represents the higher end of the range of current forecasts of ultimate potential by industry and government sources.

The forecast level of gas demand used to test the WCSB supply capability was compiled by reviewing a number of industry and government reports and reflects the future levels of demand for Canadian gas that can reasonably be expected. Specifically, Canadian domestic demand is forecast to grow at a overall average annual growth rate of 1.6 percent, and currently proposed and approved expansions of the existing transportation network will allow exports to the U.S. to grow to over 2.3 TCF per year. Total demand for Canadian gas is forecast to grow from 4.0 TCF per year in 1991 to 5.8 TCF per year in the year 2013.

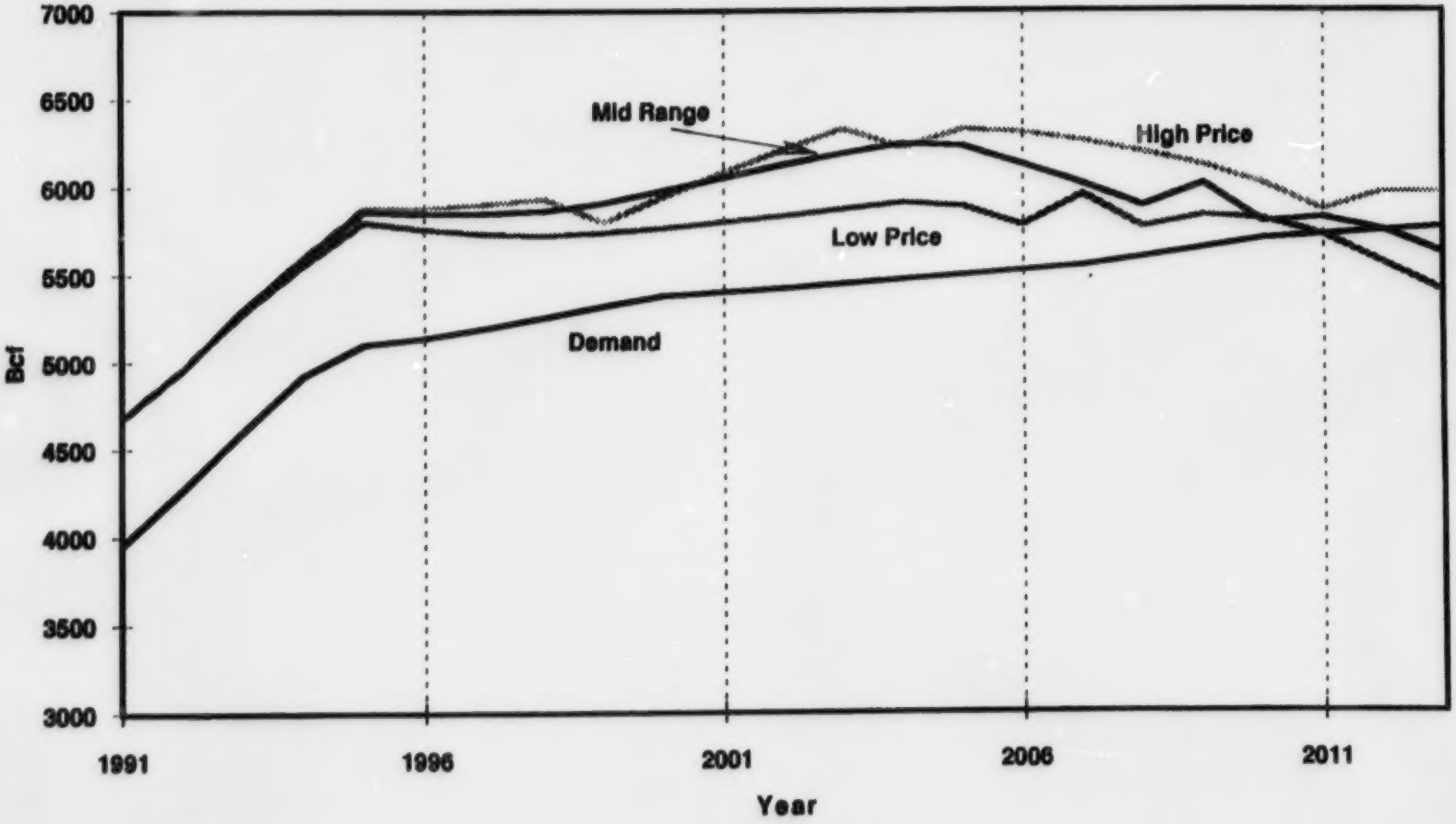
Using these demand and price assumptions and the reserves additions and drilling activity equations previously described, future drilling activity, the resultant reserves additions and productive capability were then forecast by the Sproule model. Figure 1 presents the demand forecast and the productive capability from conventional gas resources in the WCSB which is forecast to be developed under the various price forecasts.

The forecast of productive capacity determined for each price case represents the maximum sustainable productive capacity available from the WCSB. It is important to note that, in fact, the actual annual production would be somewhat less due to operational efficiencies which have been forecast at 95 percent. Therefore, the point in time where shortfalls in supply are forecast to occur would be somewhat earlier than the cross-over points exhibited on Figure 1.

The Sproule gas supply capability model predicts that, under the mid-range price forecast, the conventional gas-producing areas of the WCSB can be developed to a sufficient extent to satisfy a demand level of 5.6 TCF per year until at least the year 2008. Based on this analysis, it is clear that there will not be a significant requirement for supplemental supplies of natural gas from either coalbed methane or frontier sources until late into the next decade. However, in the event the ultimate potential of conventional natural gas resources is significantly less than the approximately 300 TCF inferred from the Sproule model, then conventional supplies will need to be supplemented at an earlier time.

FIGURE - 1

WESTERN CANADA SEDIMENTARY BASIN PRODUCTIVE CAPACITY FORECAST



ECONOMIC ANALYSIS

Potential investors in coalbed methane developments depend on an economic analysis using the discounted cashflow method to value the opportunity. Outlined in the following sections are the parameters utilized in preparing a forecast of cashflow related to the hypothetical coalbed methane developments.

RESERVES

The San Juan Basin offers a range of coalbed methane developments from which to model similar potential developments for the WCSB. This paper presents two development cases which are applicable to the San Juan Basin and which are deemed to be reasonable for the WCSB.

Table 1: Coalbed Methane Reservoir Parameters

	Low Reserve Case	High Reserve Case
Gas Content (SCF/Ton)	350	350
Coal Density (Tons/Ac.Ft.)	1,850	1,850
Drainage Area (Acres)	320	320
Approximate Coal Thickness (Ft.)	15	25
Recovery Factor	25	50
Recoverable Gas-in-Place (MMCF/Well)	850	2,750
Recoverable Gas-in-Place (BCF/Section)	1.7	5.5

The coalbed methane reserve cases (low and high) are not intended to imply that recoverable gas-in-place is related to depth. In the WCSB, it relates to shallow development in an accessible area (plains) versus deeper development in a less accessible area (foothills). In the San Juan Basin, the shallow development relates to the central and southern portion of the basin, whereas the deeper development relates to the northern portion of the basin.

The low reserve case estimate was based on drilling depths ranging from 2,000 to 3,000 feet. The well's initial rate was projected to be 50 MCF per day, increasing over 24 months to 200 MCF per day. The well's productivity was held constant at 200 MCF per day for 2 years and then declined gradually at approximately 10 percent per year to the economic limit. The life of the reserves was projected to be 24 years.

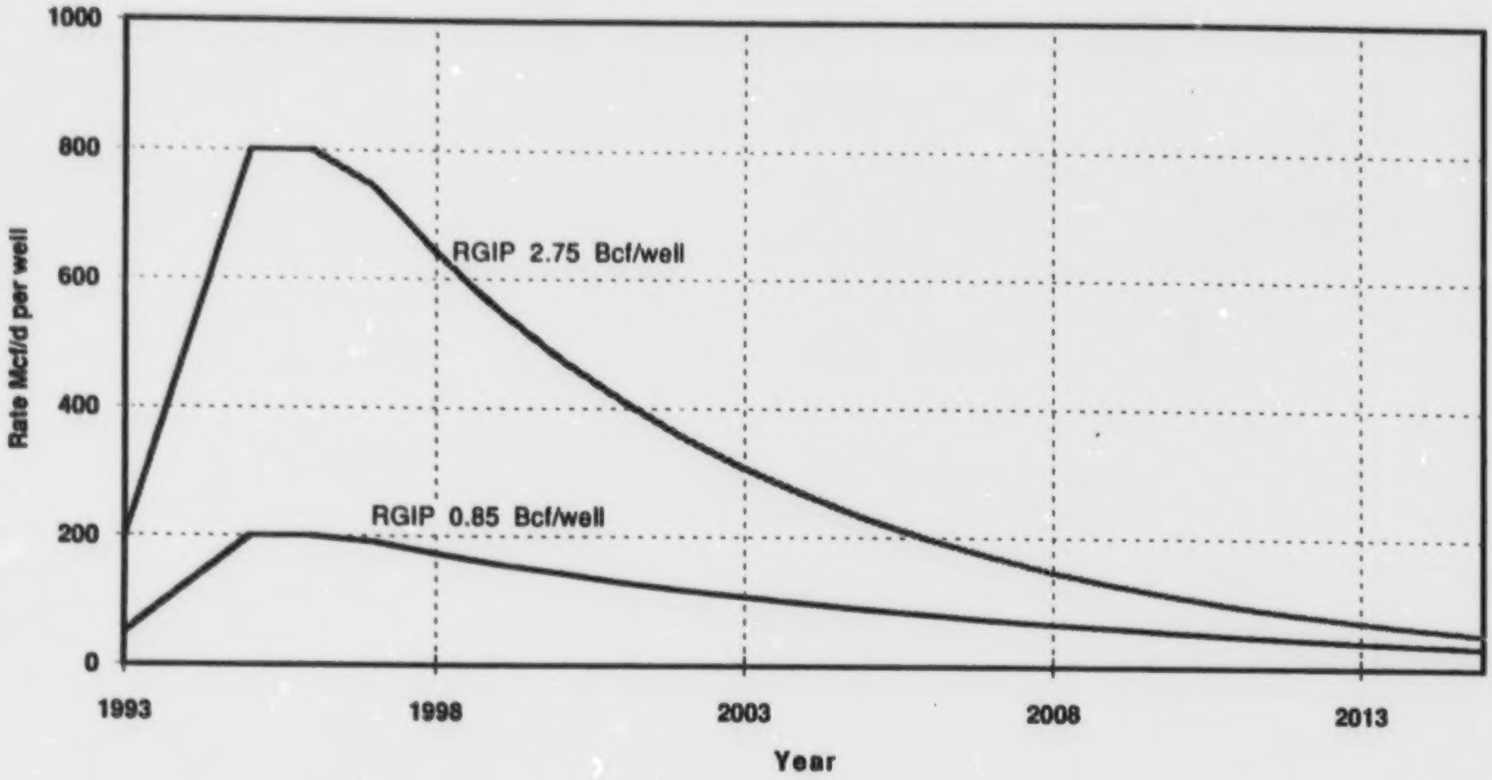
The high reserve case estimate was based on drilling depths ranging from 4,000 to 5,000 feet. The well's initial rate was projected to be 200 MCF per day, increasing over 24 months to 800 MCF per day. The well's productivity was held constant at 800 MCF per day for 2 years and then declined gradually at approximately 15 percent per year to the economic limit. The life of the reserves was projected to be 27 years.

The coalbed methane production profile (rate versus time) for each of the reserve cases is presented in Figure 2.

The reserve models for each of the basins (low and high cases) were incorporated into two on-production scenarios. The first on-production scenario utilized development in 1992 with production commencing in January 1993. The second on-production scenario was developed from the supply/demand projections presented previously. In order to meet the anticipated demand in the year 2008, it was assumed that development of coalbed methane would be initiated several years earlier. Thus, a scenario utilizing a development in 2004 with production commencing in January 2005 was used.

FIGURE - 2

COAL BED METHANE PRODUCTION PROFILE



GAS CONTRACTS

The gas contract prices for each of the basins was based on the current price in that market, assuming a contract with a 100 percent load factor. The current gas prices in the WCSB, for contracts having a high load factor, are presently substantially below the long-term contract gas prices. The forecasts of spot gas prices for Alberta and British Columbia, as prepared by Sproule, were incorporated into the WCSB economics.

The Alberta gas price for 1993 of $0.95 (CDN) per MCF was based on Sproule's projection of the spot market. The Alberta gas price for the year 2005 was projected by Sproule to be $4.50 (CDN) per MCF.

The British Columbia gas price for 1993 of $0.76 (CDN) per MCF was based on Sproule's projection of prices in the spot market. The British Columbia gas price for the year 2005 was projected by Sproule to be $4.44 (CDN) per MCF. The forecast of gas prices used for Alberta and British Columbia economics approximate the mid-range forecast used in the supply/demand model and are presented in Table 2.

The San Juan Basin gas price for 1993 was assumed to be $1.50 (U.S.) per MCF. The San Juan Basin gas price for the year 2005 was projected by Sproule to be $5.05 (U.S.) per MCF. The forecast of gas prices used for the San Juan Basin economics is presented in Table 2.

Table 2. Forecast of Gas Prices for High-Load Factor Contracts

Year	San Juan ($US/MMBTU)	Alberta ($CDN/MMBTU)	British Columbia ($CDN/MMBTU)
1993	1.50	0.95	0.76
1994	1.66	1.11	0.95
1995	1.86	1.31	1.19
1996	2.13	1.58	1.47
1997	2.48	1.93	1.82
1998	2.87	2.32	2.22
1999	3.31	2.76	2.67
2000	3.72	3.17	3.09
2001	4.01	3.46	3.38
2002	4.25	3.70	3.62
2003	4.50	3.95	3.88
2004	4.77	4.22	4.15
2005	5.05	4.50	4.44

Thereafter, the gas prices in each market were forecast to escalate at five percent per year for the life of the reserves.

The gross heating value of the coalbed methane was assumed to be 1,000 BTU's per SCF.

CAPITAL COSTS

The capital costs in each of the basins were based on actual and/or estimated cost data for wells drilled and completed to the expected depths, for the lease facilities, gathering infra-structure, and central treating and water-handling facilities. The costs are presented on a per well basis and are divided into tangible and intangible portions for tax treatment. The capital costs (Table 3) are presented on a per well basis and assume some economies of scale will be achieved with a multi-well development program.

Table 3: Drilling, Completion and Facilities Costs Per Well ($1992)

	San Juan			Alberta and British Columbia		
Reserve Case	Tang. M$US	Intang. M$US	Total M$US	Tang. M$CDN	Intang. M$CDN	Total M$CDN
Low	150	225	375	150	250	400
High	300	350	650	300	500	800

The capital costs were escalated at five percent per year after 1992 to the year in which the development costs were incurred.

OPERATING COSTS

The lease operating costs were estimated for pumping conventional wells in the WCSB and for producing coalbed methane wells in the San Juan Basin. Higher lease operating costs were used for the first 24 months to reflect the additional costs during the dewatering period. After the dewatering period, the lease operating costs were reduced. The operating costs (Table 4) are presented on a per well basis and assume a multi-well operation.

Table 4: Lease and Facilities Operating Costs ($1992)

Reserve Case	First 24 Months Lease Costs ($/Well/Month)	Thereafter Lease Costs ($/Well/Month)	Facilities Costs ($/MCF)
San Juan ($US)			
Low	2,250	1,500	0.10
High	3,000	2,000	0.10
Alberta & British Columbia ($CDN)			
Low	2,500	1,750	0.10
High	3,500	2,500	0.10

The operating costs were escalated at five percent per year after 1992 to the year in which the costs were incurred.

ROYALTY PAYMENT TO THE MINERAL OWNER

In the San Juan Basin, the majority of the mineral rights are owned by freeholders. The royalty to the mineral owner was estimated to be 17.5 percent of gross production.

In Alberta and British Columbia, the majority of the mineral rights are owned by the province. The royalty payment in the Province of Alberta is based on the price received and the monthly production volume. The royalty payment in the Province of British Columbia is based on the price received. The evaluation model calculates the provincial royalty payable as production volumes change and prices increase in the future.

A gas cost allowance of $0.30 per MCF in 1992 was charged against the Crown royalty share of production and credited to the investor for the WCSB developments.

INCENTIVE CREDITS

The incentive scheme in the U.S., that applies to coalbed methane, is referred to as the Unconventional Fuel Tax Credit. The credit was established as part of the Crude Oil Windfall Profits Tax Act as a means of encouraging the development of unconventional energy resources. These resources consisted of gas in tight sands, methane from coal seams, oil from shales, and tar sands development. The credit was recently extended in the October 1990 budget passed by Congress. The credit will now apply to wells drilled prior to December 31, 1992 for coalbed methane development. The production from eligible wells will receive the credit until the program expires on December 31, 2002.

The Unconventional Fuel Tax Credit in 1990 was $0.89 per MMBTU. The credit was estimated to be $1.00 per MMBTU in 1993. Thereafter, the credit was escalated at four percent per year until the year 2002. This assumption assumes that oil prices will not increase to a level that results in a partial or complete phase-out of the credit.

The Alberta Royalty Tax Credit (ARTC) is part of the Alberta Petroleum Exploration Plan and is available to Alberta oil and gas producers. A new five-year ARTC program became effective on January 1, 1990. The ARTC rate is oil-price sensitive and ranges from a maximum of 85 percent to a minimum of 25 percent, depending on the average royalty par price (APP) for crude oil set by the province. The maximum credit to an eligible company is equal to $2,500,000 times the ARTC rate.

At average par prices of less than $15.89 per STB, the ARTC rate is set at 85 percent. For average par prices between $15.89 and $33.37 per STB, a formula is used to calculate the ARTC rate. At an average par price of greater than $33.37 per STB, the ARTC is set at 25 percent. In the evaluation of the Alberta coalbed methane projects, it was assumed that the ARTC program would continue for the life of the reserves. The ARTC benefit is calculated in the economic model as an income tax exempt incentive.

TAXES

A severance tax rate of five percent and an ad valorem tax rate of five percent in 1993 were assumed for the State of Colorado. State income taxes in Colorado of 5.3 percent in 1993 were used. The federal income taxes in the U.S. in 1993 were assumed to be 36 percent. These rates were assumed to be constant for the life of the reserves.

The Canadian federal income taxes were calculated using a 28.84 percent rate. The provincial income taxes were calculated using a 15.5 percent rate for Alberta and a 15 percent rate for British Columbia. These rates were assumed to be constant for the life of the reserves.

PROFITABILITY INDICES

The profitability indices calculated for each development case were payout period before income taxes, discounted cashflow rate-of-return (DCFROR) before and after incomes taxes. The DCFROR for the San Juan Basin cases were presented both before and after the Unconventional Fuel Tax Credit was applied. The after-tax economics assumed a fully taxable entity. The economics for the San Juan Basin cases assumed that the Unconventional Fuel Tax Credits are utilized in each year and the investor is not subject to the alternative minimum tax.

Table 5: Comparison of Coalbed Methane Reserve Developments

Development Date	San Juan Basin Low	San Juan Basin High	Alberta Basin Low	Alberta Basin High	British Columbia Basin Low	British Columbia Basin High
Payout Period (Years) (Before Taxes)						
January 1993	6.9	4.2	8.0	5.2	8.8	5.5
January 2005	4.9	3.2	4.9	3.5	5.5	3.6
DCFROR (Percent) (Before Taxes)						
January 1993	17.6	39.6	14.4	27.3	11.3	25.4
January 2005	25.6	58.7	24.2	44.7	20.0	43.1
DCFROR (Percent) (After Taxes) Without Credit						
January 1993	16.4	35.6	12.8	23.2	9.1	21.3
January 2005	23.4	51.3	20.4	35.5	15.6	33.6
With Credit						
January 1993	34.0	66.8	N/A	N/A	N/A	N/A
January 2005	N/A	N/A	N/A	N/A	N/A	N/A

CONCLUSIONS

The potential for coalbed methane development in the WCSB is limited in the near-term by economic constraints due to low wellhead gas prices, an excess supply of conventional natural gas, pipeline constraints for exports and the lack of government incentives.

The excess supply of conventional natural gas is projected by the supply/demand model to disappear as early as the year 2005. At this point in time, pipeline capacity for domestic and export markets should be available. Also, projections of future gas prices in the year 2005 are sufficient to justify coalbed methane development in the WCSB, even if incentives are not available.

A comparison of the San Juan Basin developments indicates that currently the Unconventional Fuel Tax Credit is required for the low reserve case, but that the high reserve case is economic without the credit. It should be noted that the after-tax rate-of-return is actually higher for development in 1993 with the credit than it will be for development in the year 2005 after the credit has expired.

The low reserve case developments in the WCSB are uneconomic for development in 1993 based on the before-tax payout period and after-tax rate-of-return. The high reserve case in 1993 may be economic if the land and exploration costs required for the development are not substantial.

The WCSB developments in the year 2005 for the low reserve case have improved economic returns, but would still be considered marginal after land and exploration costs are included. The high reserve case has economic returns which would be considered acceptable to an investor.

In conclusion, significant coalbed methane development in the WCSB will not occur until the next decade without an incentive scheme similar to the U.S. Unconventional Fuel Tax Credit. The excess supply of conventional gas until at least the year 2005 in the WCSB will mean that incentive schemes for coalbed methane development are not likely to be introduced. However, a significant coalbed methane development in the WCSB in the first decade of the 21st century appears to be very realistic based on: the projections by the supply/demand model, that conventional natural gas will be unable to meet domestic and export requirements; and, the increased economic returns due to improved wellhead gas prices.

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NOTES

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ABSTRACT

Research studies have been initiated to assess the coalbed methane potential of Kootenay Group coals in southeast British Columbia. Initial efforts have been directed towards the establishment of a database of gas desorption and gas capacity curves for the coals in this region. Coal samples from three boreholes in the Elk Valley coalfield were studied for in situ gas content, potential gas capacity and petrographic characteristics.

Coal exploration boreholes drilled from the footwall of the No. 16 seam penetrated the lower 400 m of the Kootenay Group. Four major seams (seams no. 10, 5, 3 and 1) intercepted at depths of approximately 100 m, 180 m, 280 m and 387 m respectively were tested for coalbed methane content. Gas desorption results suggest much of the coalbed methane gas has desorbed and dissipated, however, gas isotherm curves indicate that the coals have the capacity to contain significant amounts of coalbed methane. Petrographic analyses of the coal samples reveal that the coals are medium volatile bituminous in rank. The relationship between low gas contents and local geological conditions such as hydrogeology and proximity to outcrop are examined.

INTRODUCTION

The Institute of Sedimentary and Petroleum Geology has initiated a coalbed methane research program for the Western Canada Sedimentary basin. This program consists of several projects designed to assess the coalbed methane potential of specific coal-bearing formations in the basin. One of these projects is the establishment of gas desorption and gas capacity curves which may or may not be significantly different form those developed for coals of other ages in other basins. Fresh coal samples from coal-bearing strata of Early Cretaceous to Tertiary age for the basin are analysed for gas desorption, adsorption isotherms, maceral analyses and quality analyses. Data are obtained by participating in joint venture projects with private industry and other government agencies for specific exploration programs throughout British Columbia and Alberta.

The first of these joint research projects entailed the sampling of lower Cretaceous Kootenay Group coals from the Elk Valley coalfield (Greenhills mine) in southeast British Columbia during the summer of 1991 (Fig. 1). Four deep (maximum depth 450 m) exploration boreholes within the open pit mine were drilled and tested for coalbed methane. This paper presents the data and analytical discussion of the results from this coalbed methane research project.

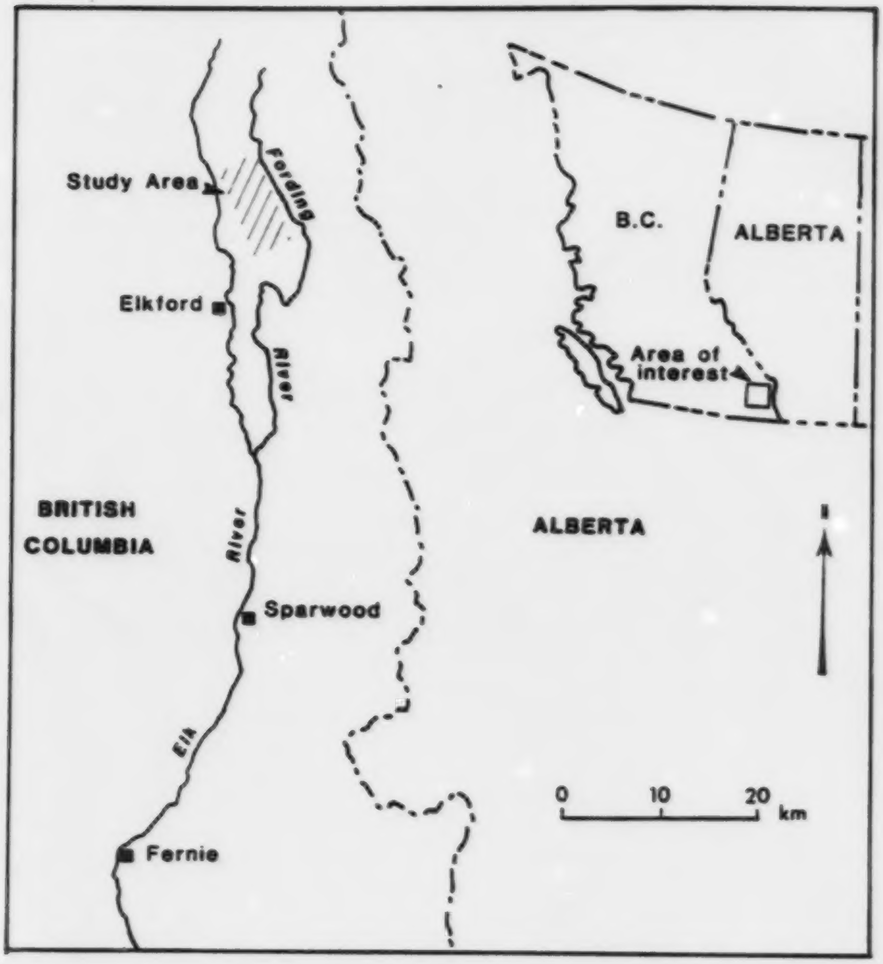
Study Area
Fording
Elkford
River
BRITISH COLUMBIA
River
Sparwood
Elk
Fernie
ALBERTA
B.C.
ALBERTA
Area of interest
0
10
20
km

Fig. 1: General location map, Greenhills coalbed methane research project.

STRATIGRAPHY

The lower Cretaceous Mist Mountain Formation of the Kootenay Group contains extensive coal resources in southeast British Columbia. In the Elk Valley coalfield the Mist Mountain Formation is in excess of 650 m thick and contains up to 75 m of coal distributed within up to 30 coal zones (Gibson, 1985). Individual seams are up to 15 m in thickness (normal stratigraphic thickness). The coal seam nomenclature within the Mist Mountain Formation is not standardized and varies between companies. The nomenclature applied to the strata sampled for this coalbed methane is study illustrated in Figure 2.

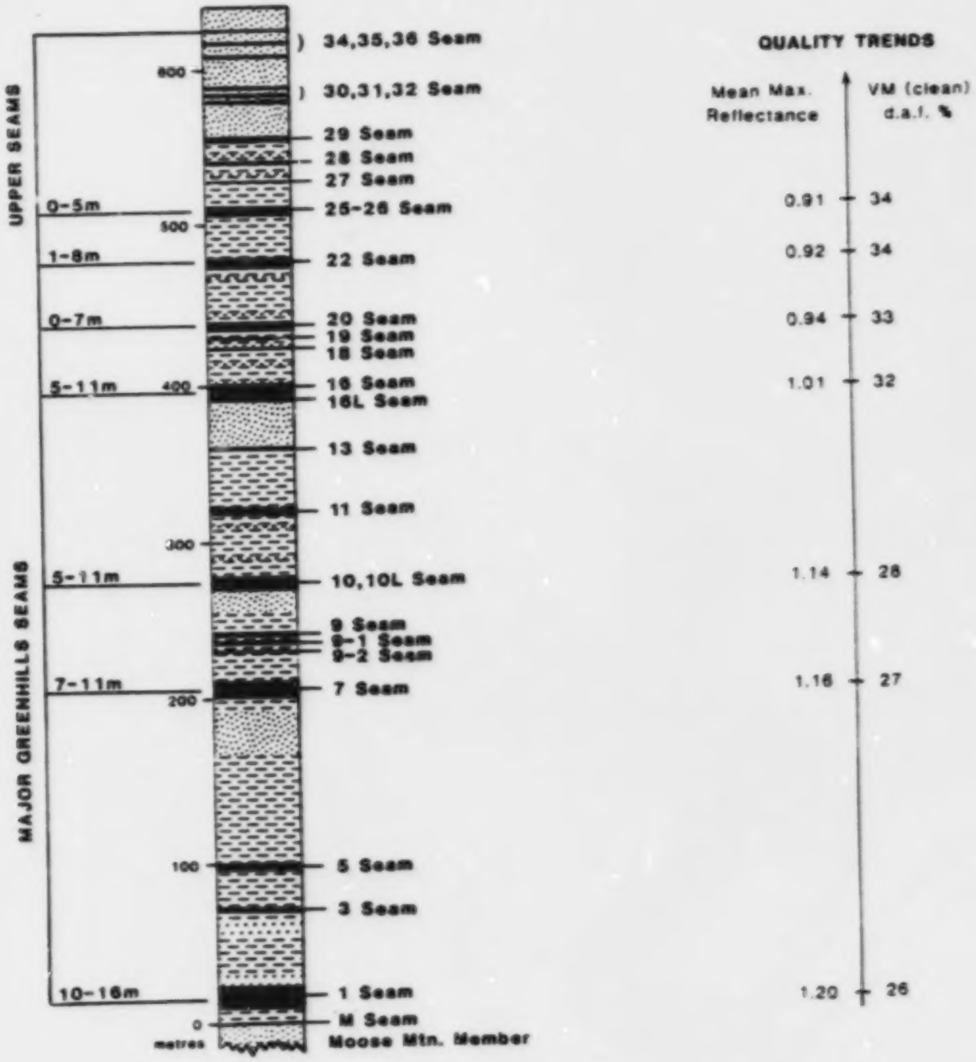
34,35,36 Seam
30,31,32 Seam
29 Seam
28 Seam
27 Seam
25-26 Seam
22 Seam
20 Seam
19 Seam
18 Seam
16 Seam
16L Seam
13 Seam
11 Seam
10,10L Seam
9 Seam
9-1 Seam
9-2 Seam
7 Seam
5 Seam
3 Seam
1 Seam
M Seam
Moose Mtn. Member
600
500
400
300
200
100
0
metres
UPPER SEAMS
MAJOR GREENHILLS SEAMS
0-5m
1-8m
0-7m
5-11m
5-11m
7-11m
10-16m
QUALITY TRENDS
Mean Max. Reflectance
VM (clean) d.a.f. %
0.91 34
0.92 34
0.94 33
1.01 32
1.14 28
1.16 27
1.20 26

Fig 2: Detailed coal seam stratigraphy of the Mist Mountain Formation at the Greenhills mine (from Westar Mining Ltd.)

In the Greenhills deposit, the major coal seams that contribute to the resource base are seams 28, 27, 22, 20, 16, 11, 10, 7, 5 and 1 (Samuelson, pers. comm.). Detailed bed by bed sampling for future analytical work was conducted on all of these coal seams. This paper will address the coalbed methane potential of the coals in the lower part of the stratigraphic succession, seams 10, 7, 5 and 1 (Table 1). These coal beds lie at approximately 270 m, 200 m, 100 m, and 10 m respectively above the basal Morrissey Formation (Plate 1).

Table 1: Summary of coal seam thickness intersected in coalbed methane exploration program.

COAL SEAM	RANGE OF THICKNESS (M)	AVERAGE THICKNESS (M)
1	12 -- 40	15
5	1 -- 3	2
7	4 -- 9	6
10	4 -- 10	8

Plate 1: Outcrop of Mist Mountain Formation at the Greenhills Mine. Seam 1 (base), 5, 7 and 10 (at top of escarpment) are exposed. Seam 5 is approximately 3 m thick.

STRUCTURE

The Elk Valley coalfield lies in the main ranges of the southern Rocky Mountains. Strata are highly folded and faulted forming a series of northwest trending synclinal structures separated by high angle reverse and normal faults (Pearson and Grieve, 1980). Thickness and distribution of the coal seams are commonly affected by similar geological structures on a smaller scale (Plate 2).

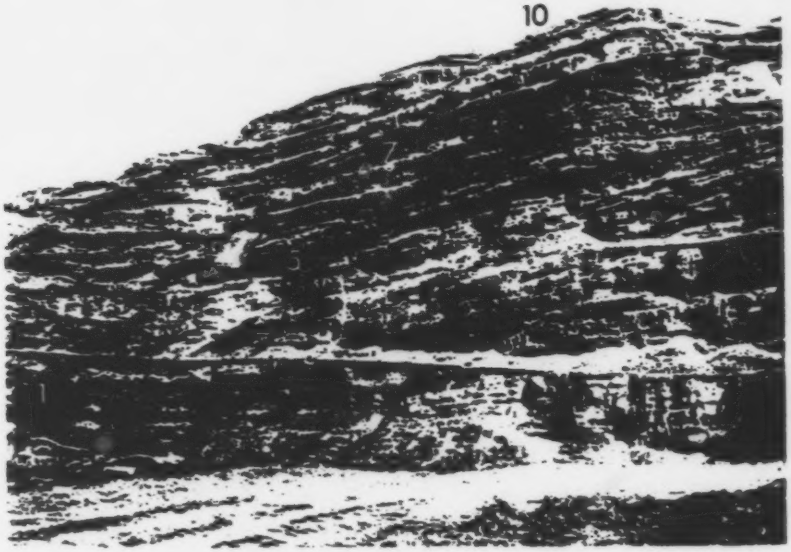

Plate 2: Small scale normal fault offsetting Seam 7, Greenhills Mine. Seam 7 is approximately 5 m thick.

The coalbed methane samples were obtained from exploration boreholes located on the western limb of the Greenhills syncline (Fig. 3). This structure is bounded on the east by the Erickson normal fault which places Lower Cretaceous rocks in contact with rocks of Permian age (Gibson and Hughes, 1981); (Fig. 4). The western limb of the structure is marked by the Greenhills Range escarpment which may represent a similar northwest trending normal fault but with lesser displacement (Samuelson pers. comm.). The south end of the syncline is cut off by obliquely trending normal faults with displacements of less than 200 m. Limbs of the syncline dip at approximately 35 degrees and the structure plunges gently to the northwest into the Fording River valley (Plate 3).

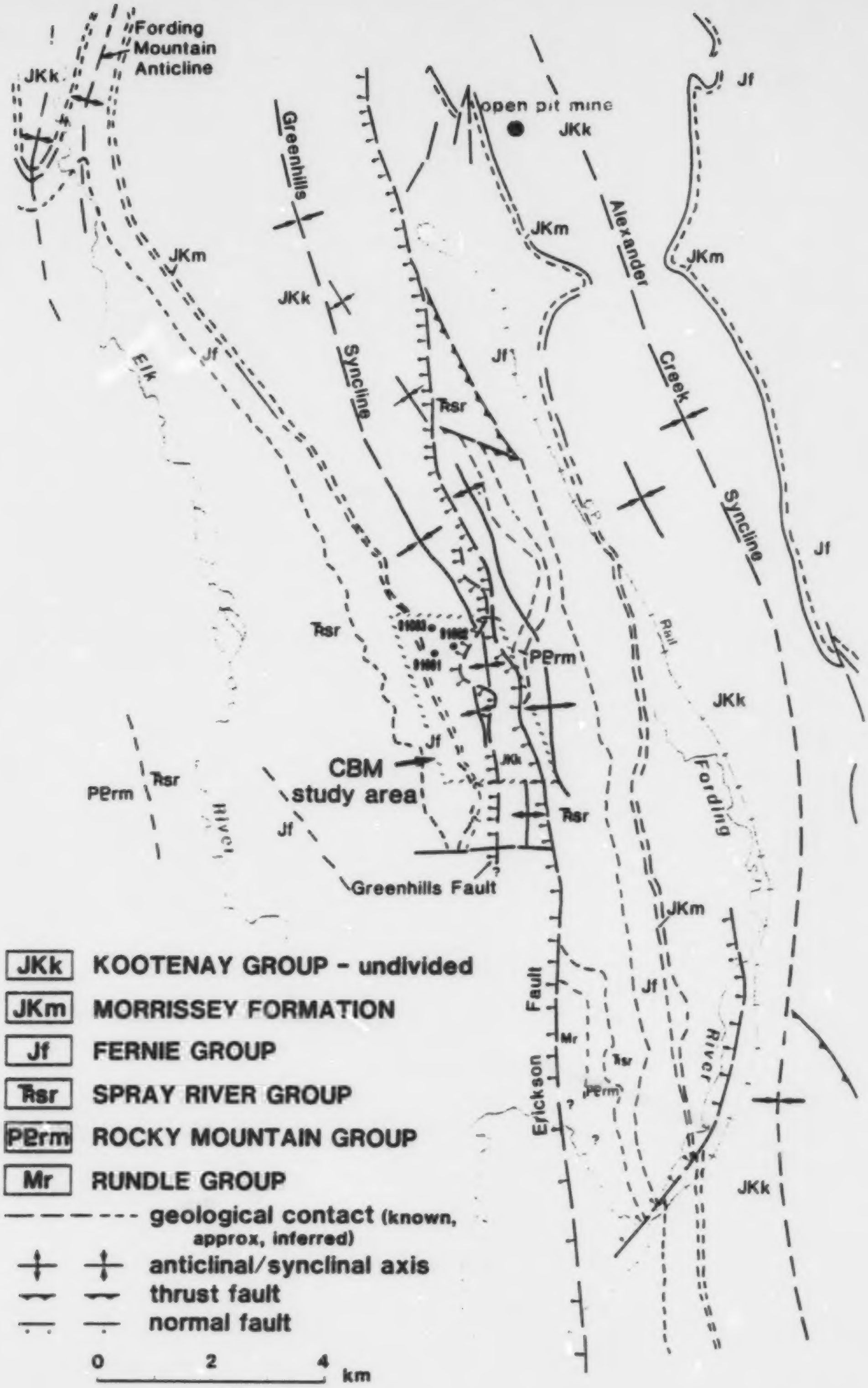
Fording Mountain Anticline
JKk
open pit mine
JKk
Jf
Greenhills Syncline
JKm
Alexander Creek Syncline
JKm
JKm
JKk
Elk
Jf
Jf
Ŧsr
Jf
Ŧsr
91003
91002
91001
Ŧsr
PPrm
JKk
Jf
CBM study area
JKk
Ŧsr
PPrm
Ŧsr
River
Jf
Ŧsr
Greenhills Fault
Fording
JKm
Erickson Fault
Mr
Ŧsr
PPrm
Jf
River
JKk
JKk KOOTENAY GROUP - undivided
JKm MORRISSEY FORMATION
Jf FERNIE GROUP
Ŧsr SPRAY RIVER GROUP
PPrm ROCKY MOUNTAIN GROUP
Mr RUNDLE GROUP
geological contact (known, approx, inferred)
anticlinal/synclinal axis
thrust fault
normal fault
0
2
4
km

Fig. 3: Regional geology map of the Elk Valley coalfield and the Greenhills Range. Nos. 91001, 91002 and 91003 indicate approximate postion of boreholes from which samples adsorption isotherm samples were examined for this study.

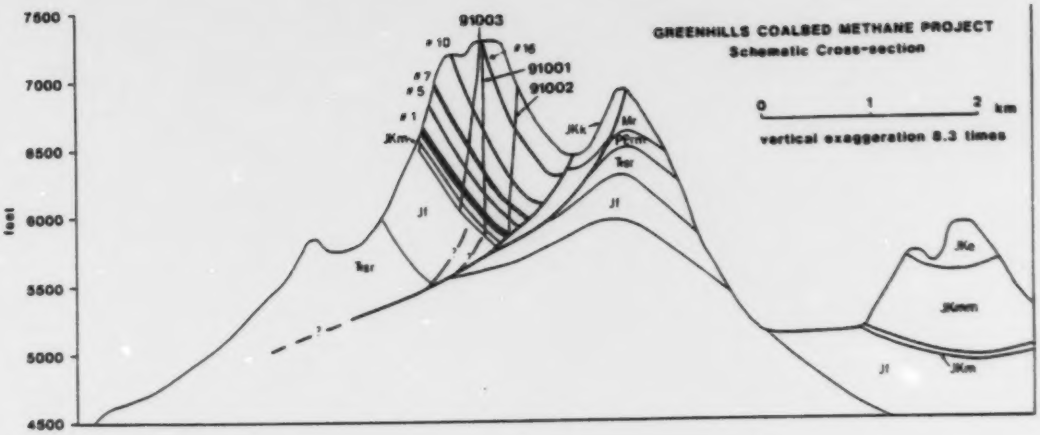
GREENHILLS COALBED METHANE PROJECT
Schematic Cross-section
0
1
2
km
vertical exaggeration 8.3 times
7500
7000
6500
6000
5500
5000
4500
feet
91003
# 10
# 16
91001
91002
# 7
# 5
# 1
JKm
JKk
Mr
Trgr
Jf
?
JKe
JKmm
JKm

Fig. 4: Schematic cross-section of the Greenhills syncline and Erickson normal fault illustrating location of exploration boreholes in relation to topography and structure.

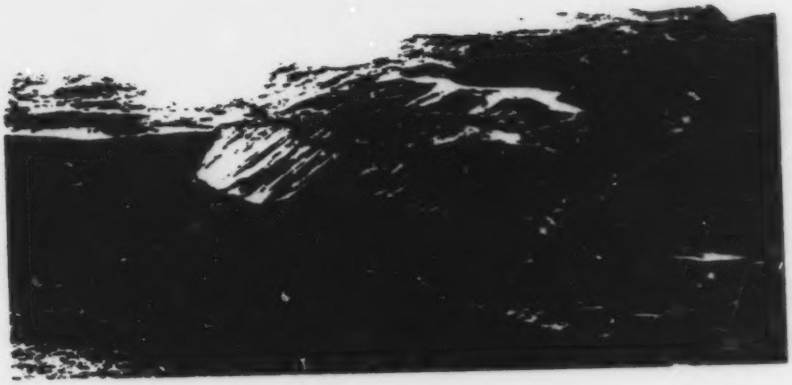

Plate 3: View of the Greenhills syncline plunging to the north from the exposed footwall of seam 16, (looking north).

Small scale folding and faulting of the coal-bearing strata occurs at or near the intersection of the obliquely trending faults, but the axis of the fold appears to be unaffected at an elevation of the upper seams. Borehole data suggest that seam 1 may be tectonically affected at depth near the axis of the fold (Fig. 4).

SAMPLING and TEST PROCEDURES

The sampling of coal cores for coalbed methane gas content was restricted to the major seams penetrated in the exploration boreholes. Coal desorption testing was conducted on seams 1,5,7 and 10. Adsorption isotherms, proximate analysis, vitrinite reflectance, maceral and equilibrium moisture content analyses were performed on two samples from seam 1 and one each from seams 7 and 10.

Coal samples were obtained from 69 mm (2.5 inch) diameter diamond core cut utilizing a standard core barrel. Depth of intersections ranged from 110 m for seam 10 to 385 m for seam 1. The deepest seam, seam 1, was considerably broken and crushed while the shallower seams, 7 and 10, were unbroken, and contained minor fracturing only. All boreholes were spudded from the footwall of seam 16. Boreholes GSC91001 and GSC91003 were drilled on the western limb of the syncline, while GSC91002 was completed near the axis of the structure.

The coal core, upon removal from the core barrel, was logged, sampled and placed within a pre-weighed, pressure tested (50 psi) desorption canister. The canisters were placed within a temperature controlled environment (22°C) and desorbed gas was measured using a water displacement biuret system equalized to atmospheric pressure. Desorption was considered complete when no gas was liberated for a period of 24 hours. Upon completion of sample desorption, lost gas calculations were conducted using the U.S.B.M. "Direct Method" (Diamond and Levine, 1981).

ADSORPTION ISOTHERM ANALYSIS

Four samples were selected for adsorption isotherm analysis, two from seam 1 at the depths 399.29 m and 395.60 m, one from seam 7 at the depth of 179.83 m, and one from seam 10 at a depth of 100.00 m. The samples were sealed in cans at the drillsite before transporting for analysis.

In preparation for Adsorption Isotherm testing, the coal samples were subjected to a crushing process followed by wet-sieving through a - 60 mesh screen. Samples were split for equilibrium moisture content, proximate analysis and adsorption isotherm analysis. For Adsorption Isotherm testing, the samples were restored to equilibrium moisture content according to the procedures described in ASTM Standard: D1412-89.

The adsorption isotherm tests were performed at a constant ambient temperature of 22°C and at seven increasing pressure levels ranging from 200 psi to 2000 psi (1379 kPa to 13,790 kPa). Prepared samples were placed individually in the test cell and the reference cell was filled with 99.97% pure methane. Control temperature and initial pressure were established and the system was allowed to stabilize for a minimum of six hours. The test cell containing the sample was evacuated followed by introduction of methane from the reference cell.

Pressure and temperature were monitored until two successive measurements were constant, indicating stabilization. These procedures were then repeated for each subsequent pressure point.

Volume of methane adsorbed was determined by the Boyles'Law technique, allowing for the variable compressibility of methane at various pressures. Gas content results were ash corrected based on data from the proximate analysis (Fig. 7). A second ash content was completed on the actual isotherm sample and these data concurred with the first set.

ANALYTICAL RESULTS

Desorption Data

Desorption tests were completed on various coal seams from the three exploration boreholes. The results are widely variable but for the most part indicate that much of the gas has desorbed from the coal prior to drill bit penetration. Seam intersections and desorbed gas contents (including lost gas estimates) are presented in Table 2.

Table 2: Measured gas volumes (not corrected for ash content.

Borehole	Seam no.	Desorbed Gas (cc)	Lost Gas (cc)	Total Gas (cc)
GSC91001	1-1	707	65	772
	1-2	1592	20	1612
	1-3	1391	300	1691
	1-4	2297	360	2657
	1-5	2376	500	2876
	7-1	129	10	139
GSC91002	7-1	127	30	157
	7-2	47	10	57
	5-1	81	0	81
GSC91003	10-1	128	18	146
	5-1	35	12	47
	5-2	40	8	48
	1-1	779	103	882
	1-2	156	112	268
	1-3	223	65	288
	1-4	701	190	891

Similar desorption tests were conducted by CANMET in 1984 at the Fording coal mine immediately to the north of the Greenhills mine (Feng et al., 1984). The CANMET boreholes were drilled along the west limb of the Greenhills syncline in a similar stratigraphic and structural position to the GSC boreholes. Depth of intersection of the same coal horizons (equivalent to seams 10,7,5 and 1) were approximately the same but elevation of the intersections were approximately 350 m lower (Table 3). A crossplot of gas content versus depth of intersection indicates a general trend of increases gas content versus depth of intersection, The GSC borehole data has the lowest gas contents for coals that were intersected at the greatest depths (Fig. 5). Comparing gas content versus elevation reveals that at an elevation of approximately 1600 m, desorbed gas content increases dramatically for seams 7, 5 and 1 or equivalents (Fig. 6). This elevation corresponds to the elevation of the Fording River located immediately to the east. It is probable that the regional water table as defined by the elevation of the Fording River valley provides the formational pressure regime enabling coalbed gas to be retained within the coal seam. Gas contents of coals that lie above the valley floor will tend to be lower than those below.

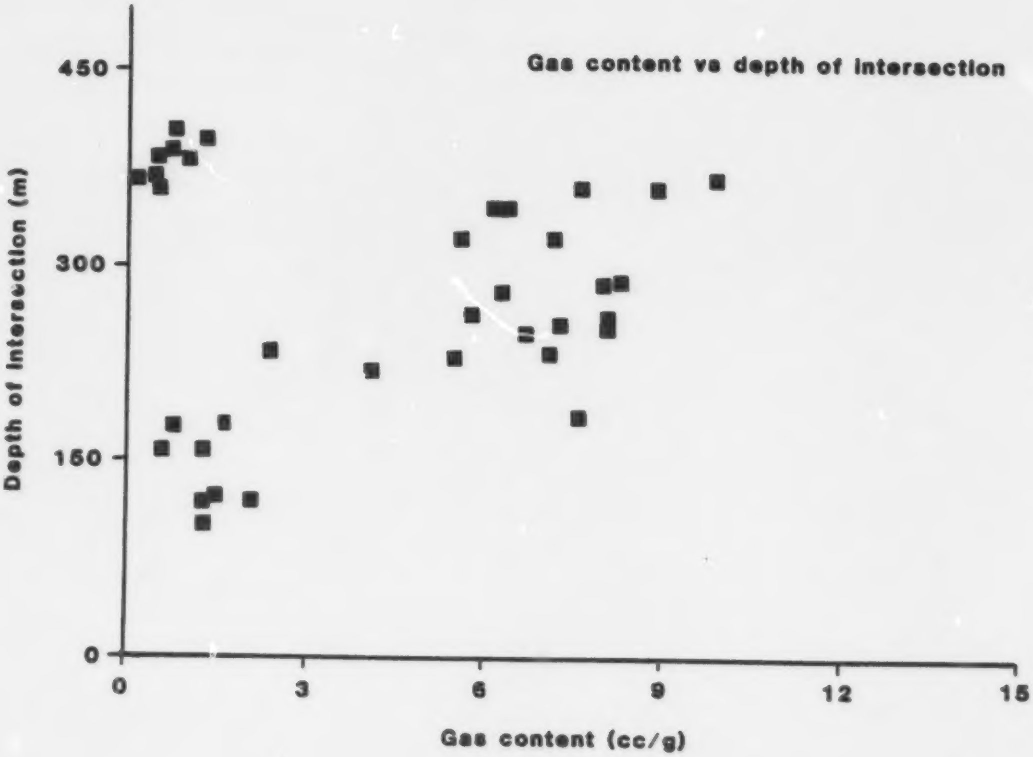

Fig. 5: Crossplot of gas content versus depth of intersection of coal.

Table 3: Comparison of gas content versus depth of intersection and elevation.

Borehole	Seam No.	Depth (m)	Elevation (m)	Gas Content (cc/g)
91001	1-1	380	1815	0.47
	1-2	381	1814	1.03
	1-3	387	1808	0.73
	1-4	396	1799	1.31
	1-5	400	1795	0.76
91003	1-1	360	1835	0.50
	1-2	363	1832	0.14
	1-3	366	1829	0.14
	1-4	369	1826	0.40
DDH1340	B(1)-1	319	1454	7.17
	B(1)-2	320	1453	5.61
	E(5)-1	218	1555	4.09
	E(5)-2	230	1543	5.50
	E(5)-3	231	1542	7.08
	E(5)-4	233	1540	2.40
	F(7)-1	102	1671	1.30
	F(7)-2	119	1654	1.30
	F(7)-3	120	1653	2.10
	F(7)-4	122	1651	1.50
DDH1341	B(1)-1	343	1507	6.44
	B(1)-2	344	1506	6.14
	E(5)-1	249	1600	6.70
	E(5)-2	252	1597	8.10
	E(5)-3	255	1594	7.30
	E(5)-4	259	1590	8.10
	E(5)-5	262	1587	5.80
	F(7)-1	157	1693	1.30
	F(7)-1	158	1692	0.60
DDH1342	B(1)-1	357	1491	7.65
	B(1)-2	358	1490	8.94
	B(1)-3	364	1484	9.94
	E(5)-1	280	1568	6.30
	E(5)-2	282	1566	7.60
	E(5)-3	285	1563	8.00
	E(5)-4	287	1561	8.30
	F(7)-1	175	1673	0.80
	F(7)-2	177	1671	1.60

Note (1): Boreholes 91001, 91002 and 91003 were drilled by Westar Mining Ltd. and were sampled by the GSC in 1991. Boreholes DDH1340, DDH1341 and DDH1342 were drilled and sampled by CANMET in 1984.

Note (2): Volumes of gas measured for coal seams intersected in Borehole 91002 were minimal and no gas conents were calculated.

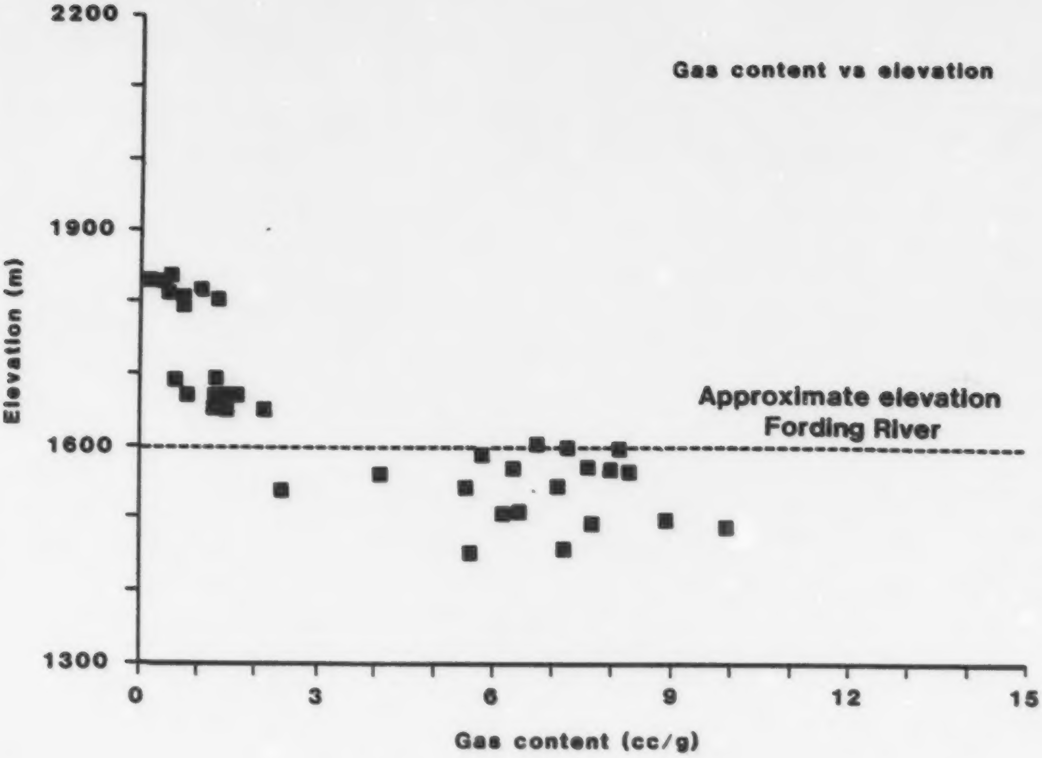

Fig. 6: Crossplot of gas content versus elevation of coal intersection.

Adsorption Isotherm Data

Results of the adsorption isotherm tests (Fig. 7), indicate the coal seams tested are capable of storing much greater quantities of methane gas than observed in the field desorption tests. At the depths seams 10, 7, 5 and 1 were intersected, ash corrected adsorption values were calculated using reservoir pressures determined by a pressure gradient (Table 4). Under these parameters, the potential gas content for Seam 1 could be as high as 363 scf/ton (11.3 cc/g) at a depth of 350 m. Several of the borehole intersections of the CANMET data approach these levels at shallower depths, suggesting that it may be possible to have a 100 percent saturated reservoir or perhaps even an overpressured reservoir under suitable hydrological conditions. Measured gas contents of the GSC borehole samples tended to be substantially lower than the projected values for the specific depth of intersection. This is probably due to the location of the boreholes themselves. The boreholes drilled on the Greenhills mining property were planned to assess the potential of open pit mine expansion. As such the holes have been located to intersect the coal seams near the subcrop line of the seams along the Elk Valley escarpment to the west. All seams intersected outcrop along this escarpment within close proximity to the

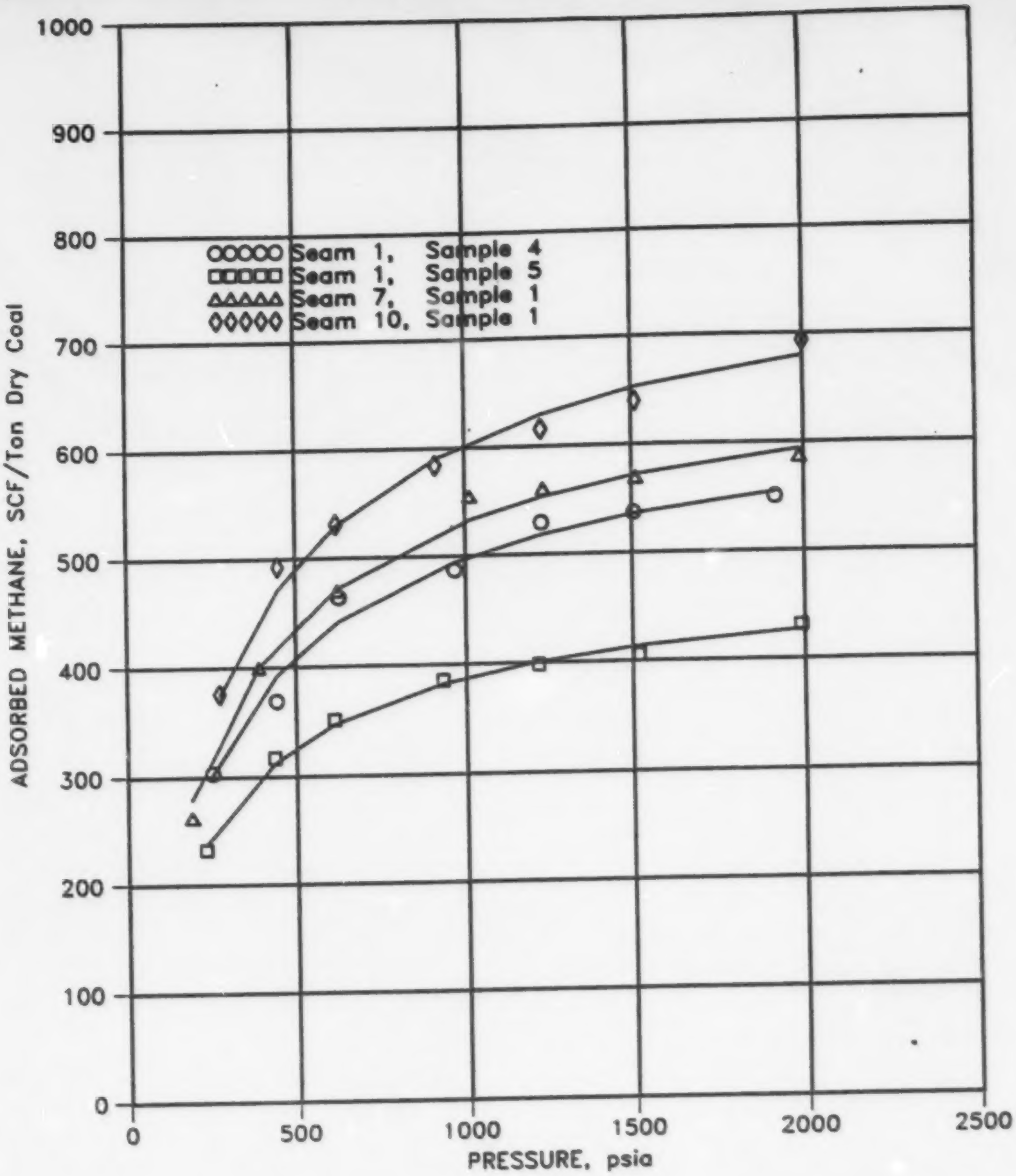

Fig. 7: Methane adsorption versus pressure for 4 coal seam samples from Westar boreholes. Curves have been ash corrected and adsorption was completed at reservoir temperature of 22 C.

position of the borehole intersection. It is probable that most of the gas that may have been present within the coals has desorbed up dip to the outcrop and dissipated into the atmosphere. Seams 10, 7 and 5 all were intersected above the local water table and the low volumes of desorbed gas reflect this factor. Even the desorption values obtained for Seam 1, (which lies below the perched structural water table of the Greenhills syncline) are substantially lower, suggesting that reservoir pressures at 1800 m are insufficient to retain the gas in formation. This may be in part due to the highly fractured nature of the coal within Seam 1.

Table 4: Coal Petrography, Proximate analysis and Adsorption/Desorption Data for GSC Borehole Coal Samples.

				PROXIMATE ANALYSIS					MACERALS WT % MMFB						
Sample	Depth (m)	Reservoir Pressure (psia)	Desorption Temp (°C)	Volatile Matter Wt % Air Dried	Fixed Carbon Wt % Air Dried	Water Wt % Air Dried	Ash Wt % Air Dried	Ro Max.	Vit.	Lip.	Inert.	E.Q. Moist Wt %	Mineral Matter Wt %	Adsorbed CH_4 @ Res. Pres. scf/ton Ash Cor.	Desorbed CH_4 scf/ton Ash Cor.
Seam 1 Sample 4	393.00	386	22°C	23.11	64.29	0.61	11.99	1.20	51.1	0.0	48.9	1.5	3.2	363	48
Seam 1 Sample 5	399.29	389	22°C	21.55	54.74	0.58	23.13	1.19	60.5	0.0	39.9	1.8	24.4	296	55
Seam 7 Sample 1	170.83	146	22°C	27.01	65.03	0.75	7.21	1.15	57.0	2.8	40.2	2.1	3.0	258	3
Seam 10 Sample 1	108.00	93	22°C	25.40	70.19	0.76	3.65	1.14	56.4	1.0	42.6	2.9	1.0	188	2

PETROGRAPHIC ANALYSIS

Petrographic and maceral analysis were conducted on the four coal samples upon which adsorption isotherms were completed. Results of these studies are summarized in Table 4. Reflectance values indicate that all four seams studied are medium volatile bituminous rank with Ro%max ranging from 1.14% for seam 10 to 1.20% for seam 1. Vitrinite and inertinite contents are variable ranging between 51.1% to 60.5% for vitrinite and 39.9% to 48.9% for inertinite. The narrow range of reflectance and maceral variability suggest that the wide range in gas capacity curves may be due to some other variable. Examination of mineral matter content indicates that there is a strong correlation between increasing mineral matter (1.05% to 24.4%) and decreasing gas capacity.

Both samples 1-4 and 1-5 appear to be highly crushed with a high degree of microbrecciation. Similar observations were made in the sampling of the cored intervals. Seams 10, 7, and 5 tend to be moderately cleated but very blocky. Seam 1 on the other hand is highly crushed and sheared. The physical characteristics of the coal may control to some extent the adsorptive capacity of gas within the coal seam. The gas capacity differences between seam 1-4 and 1-5 are probably due to the mineral matter content. Further work relating gas capacity to size fraction is needed to determine the impact sheared coal has on the reservoir properties.

CONCLUSIONS

Coalbed methane desorption and adsorption experiments undertaken from coal samples in the Greenhills coal deposit in southeast British Columbia indicate that the coals, even though minimal gas was observed in the desorption tests, have the capacity to retain significant quantities of coalbed methane under favourable reservoir conditions. Regional hydrological conditions relating to topography and the elevation of the Fording River appear to control the retention of gas within the formation. Variations of gas capacity between coals of different seams may be controlled by the composition and physical characteristics of the coal itself. Further work is required to assess the potential of the region based upon the results presented in this paper.

ACKNOWLEDGEMENTS

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NOTES

COALBED METHANE PRODUCTION FROM THE POTTSVILLE FORMATION AT CEDAR COVE FIELD, BLACK WARRIOR BASIN, ALABAMA, U.S.A.

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Birmingham, Alabama 35203

ABSTRACT

In 1990, 1 664 wells in the Black Warrior Basin of Alabama produced approximately 1 020 MMm^3 (36 Bcf) of coalbed methane from 12 fields. The highest coalbed methane production per well is from a three field area near Cedar Cove. In July 1991, this area produced approximately 53.8 MMm^3 (1.9 Bcf) of gas from 456 wells, accounting for 33 percent of the basin's monthly coalbed methane production. Production was from three to five multiple-seam coal groups that comprise informal subdivisions of the upper Pottsville Formation (Pennsylvanian Age).

The occurrence, thickness, and trends of Pottsville depositional sequences and coal beds reflect an interplay of depositional and structural settings. Coal beds occur in coastal plain facies that overlie deltaic sediments that were deposited along a northeast-trending shoreline. Within Cedar Cove Field, the depocenter for the upper Pottsville parallels, and is near, the northeast-trending Appalachian fold-and-thrust belt, which bounds the field and the Black Warrior Basin on the southeast. Thick, northeast-trending coal deposits formed in a coastal plain setting, whereas northwest-trending coal deposits formed in a floodplain setting.

In most of the Cedar Cove area, strata dip 1° southwestward. However, in the southeast where the field is bounded by the Appalachian fold-and-thrust belt, Pottsville strata dip 65° basinward (northwestward). Northwest-striking normal faults are locally abundant. Commonly, these faults have displacements of 45 m (150 ft) and extend less than 2.4 km (1.5 mi).

Net coal thickness in the upper Pottsville Formation ranges from 9 to 15 m (27 to 50 ft). Completion depths in coalbed methane wells are 180 to 1 160 m (600 to 3 800 ft), and the rank of the lower two coal groups is medium-volatile bituminous to high-volatile A bituminous. Bottomhole pressures and temperatures range from 10 755 kPa and 39°C (1 555 psi and 103°F), in the lowest coal group, to 1 383 kPa and 18°C (200 psi and 64°F) in the highest group. Gas content of coal beds within the field ranges from 7.2 to 21.3 cc/g (231 to 681 Scf/ton).

In September 1991, average gas and water production were 3.4 Mm^3 and 55 m^3/d (122 Mcf/d and 347 bbl/d), respectively, from 407 wells in the Cedar Cove area. The primary control on coalbed methane production is net coal (reservoir) thickness. Locally, high coalbed methane production may result from structural influences; highly productive wells, which produce from 4.8 to 28.2 Mm^3/d (150 Mcf/d to more than 1 000 Mcf/d), occur along west-and northwest-trending fracture zones.

INTRODUCTION

Coalbed methane production in the Black Warrior Basin dates to 1980, when the Oak Grove Field was created. Following a slow start, the basin experienced a boom in coalbed methane development in 1989 and 1990, when 1 079 and 2 290 wells, respectively, were permitted and the number of producing wells increased to 1 197. In July 1991, 2 369 wells were producing in 13 coalbed methane fields in the basin, and four fields were awaiting production. Coalbed methane production in 1990 was approximately 1 020 MMm^3 (36 Bcf), and 1991 production will probably exceed 1 840 MMm^3 (65 Bcf).

Cedar Cove, Holt, and Peterson coalbed methane fields (Figures 1 and 2) were established in 1982-84. Because the same reservoir coal groups occur in the Cedar Cove, Holt, and Peterson fields (Figure 2), we use the term "Cedar Cove area" to include all of these fields. Coalbed methane reserves in this area are estimated to exceed 14 100 MMm^3 (500 Bcf). Initial coalbed methane development of the Cedar Cove area was slow. For example, initial development in Cedar Cove field included only 18 producing wells. However, the pace of development dramatically increased in 1989 as operators sought to take advantage of a tax incentive before the end of 1990. To date, more than 690 wells have been drilled in the Cedar Cove area. Taurus Exploration, Inc. operates more than 400 of these wells. Cedar Cove area wells are among the most productive coalbed methane wells in the basin. In July 1991, this area produced more than 54 MMm^3 (1.9 Bcf) of gas from 456 wells, accounting for 33 percent of the basin's monthly coalbed methane production.

METHODS

In the Cedar Cove area, data from geophysical logs were used to make structure, isopach, and coal-occurrence maps and cross sections. Reservoir characteristics of Pottsville coal beds were determined by testing 42 cores from 21 wells. Gas adsorption and desorption, coal composition, reservoir pressure, and in-situ permeability values were determined in laboratory and field tests. Vitrinite reflectance was measured to determine coal rank. To evaluate production, we mapped cumulative gas production for the first six months of sales and cumulative water production for the first six months on pump. Finally, these production maps were compared to geologic maps and cross sections to clarify controls on coalbed methane occurrence and producibility.

GEOLOGIC SETTING

STRUCTURAL SETTING

The Black Warrior Basin is a Paleozoic foreland basin located at the junction of two fold-and-thrust belts (Figure 1). The Appalachian fold-and-thrust belt forms the southeastern margin, and the buried Ouachita fold-and-thrust belt forms the southwestern margin of the basin. Carboniferous strata crop out at the eastern margin of the Black Warrior Basin. In the Cedar Cove area near the southeast margin of the basin (Figures 1 and 3, structural margin), these strata dip steeply northwestward along the northwest flank of the Birmingham Anticlinorium (Figure 3 and 4). Dips as steep as 65° have been recorded in dipmeter logs. This structural margin is the southeastern limit of coalbed methane production in Cedar Cove, owing to either the updip limit of economic gas contents in coal beds or drilling problems associated with steeply dipping strata. In contrast to the steeply dipping southeast margin of the field, most of the Cedar Cove area is located along the structural floor of the Black Warrior Basin (Figures 3

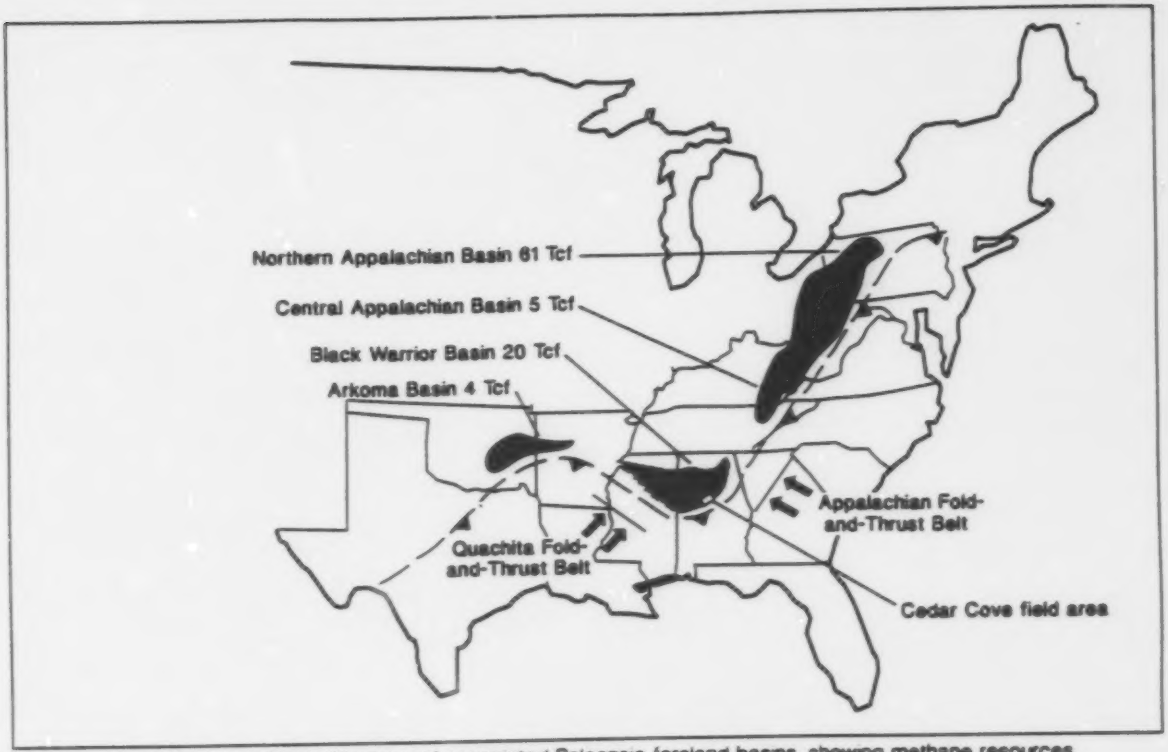
Northern Appalachian Basin 61 Tcf
Central Appalachian Basin 5 Tcf
Black Warrior Basin 20 Tcf
Arkoma Basin 4 Tcf
Appalachian Fold-and-Thrust Belt
Quachita Fold-and-Thrust Belt
Cedar Cove field area

Figure 1. Location of the Black Warrior and associated Paleozoic foreland basins, showing methane resources. Resource estimates from Kuuskraa (1989).

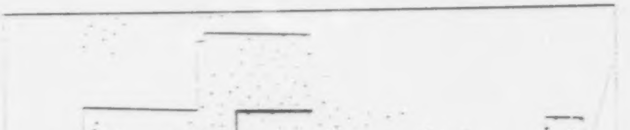
Cedar Cove Field
EXPLANATION

Figure 2. Map of Cedar Cove field area showing well locations.

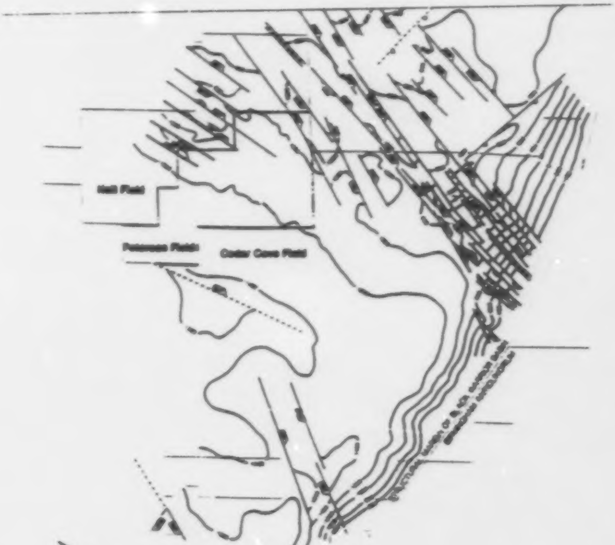
Cedar Cove Field
EXPLANATION

Figure 3. Structure map of the top of the Pratt coal group.

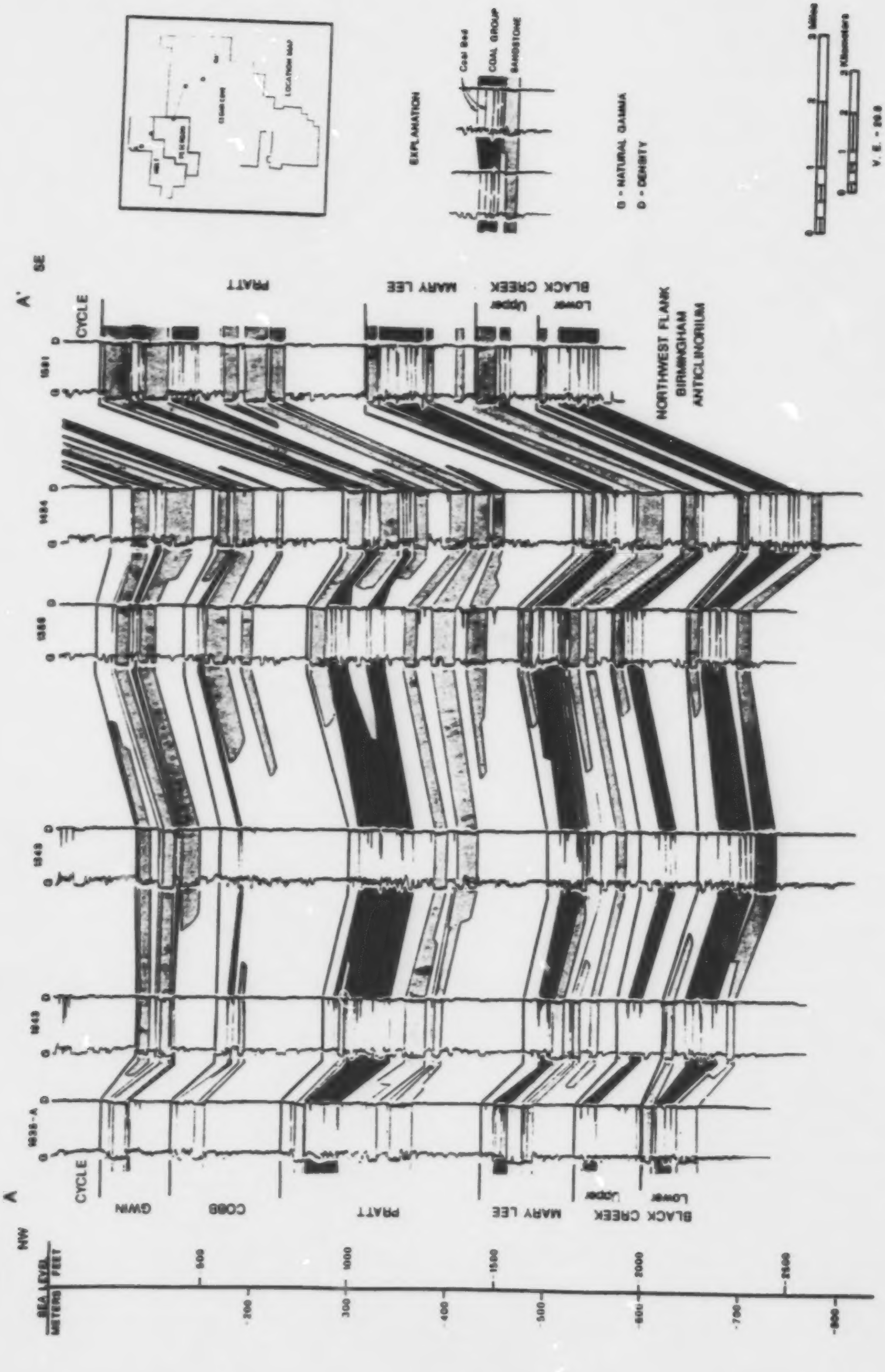
NW
A
SE
A'
SEA LEVEL
METERS
FEET
500
1000
1500
2000
2500
-200
-300
-400
-500
-600
-700
-800
CYCLE
GWIN
COBB
PRATT
MARY LEE
BLACK CREEK
Upper
Lower
G
D
NORTHWEST FLANK
BIRMINGHAM
ANTICLINORIUM
EXPLANATION
Coal Bed
COAL GROUP
SANDSTONE
G - NATURAL GAMMA
D - DENSITY
Miles
Kilometers
LOCATION MAP

Figure 4. Structural cross section A-A'.

and 4). In this area, strata dip southwestward at 1° to 2° (40 to 60 m/km [100 to 150 ft/mi]).

Important structural features in the eastern part of the Black Warrior Basin are northeast-striking folds. Thrust faults are reported to be associated with these folds in mines near the northern limits of the Cedar Cove area, but they are not common. Northwest-trending normal faults, both antithetic and conjugate, are common throughout the basin. They occur in "swarms" or in "horsetails" patterns (Thomas 1988). These northwest-trending normal faults are especially prevalent in northern Cedar Cove area (Figure 3), where they commonly have displacements of 45 m (150 ft.) and extend less than 2.4 km (1.5 miles). Maximum displacement occurs near the structural margin of the basin. Faulting is minor throughout the remainder of the Cedar Cove area, with the exception of a large, 6.6 km by 1.6 km (4 mi by 1 mi), graben in the southeastern region (Figure 3).

STRATIGRAPHY

In the Black Warrior Basin, the Pottsville Formation (Pennsylvanian) is subdivided into two informal units; the lower unit is composed predominantly of barrier bar and marine sediments, whereas the upper Pottsville is composed mainly of upward-coarsening, coal-bearing, fluvial-deltaic sediments separated by thin marine mudstones. The coal-bearing upper Pottsville is subdivided into several informal depositional sequences (cycles) that were named from their coal groups (Figures 4 and 5) (McCalley, 1900). These coal groups occur in the upper part of the 5 sequences that contain economic coalbed methane in the Cedar Cove area. Upper Pottsville sediments in the Cedar Cove area are thickest in a depocenter near the structural front. In this area, the Pottsville Formation is approximately 1,830 m (6,000 ft) thick, and upper Pottsville strata are 1 140 (3 800 ft); individual sequences are as thick as 210 m (700 ft).

A typical upper Pottsville depositional cycle in the Cedar Cove area is a regressive sequence consisting of basal fossiliferous marine shales that grade upward through thin prodelta mudstones and sandstones into interbedded continental sandstones, mudstones, and coal beds (Figures 4 and 5). The marine shale interval, as identified on geophysical logs, is generally 15 to 23 m (50 to 75 ft) thick and typically comprises less than one-third of a cycle. The fluvial-deltaic interval is as much as 30 m (100 ft) thick. The coal groups occur in the upper one-third or one-half of each cycle. Generally, coal beds are separated by thin-bedded lithologies, primarily by mudstones and sandstone that are 3 to 4.5 m (10 to 15 ft) thick.

COAL OCCURRENCE

The depositional controls on the occurrence and trends of upper Pottsville coal were established in earlier studies (Pashin and others, 1991). Upper Pottsville peat accumulated in fluvial-deltaic settings. The thickest and most continuous coal deposits trend northeastward, parallel to the paleoshoreline; secondary, northwest-trending deposits of thick coal formed in a floodplain setting. Locally, anomalously thick coal beds are attributed to peat accumulation in abandoned fluvial channels (Pashin and Sarnecki, 1990). Splitting of coal beds is common and result from either depositional or tectonic influences.

In the Cedar Cove area, the Black Creek through Gwin coal groups are potential methane targets at depths as shallow as 180 m (600 ft). Maximum depth of the Black Creek coal group is 1 160 m (3800 ft) in this area. To make coal-occurrance maps, coal thicknesses were recorded from bulk density logs. Net coal thickness in the Black Creek through Gwin coal groups is as much as 15 m (50 ft) in the Pottsville depocenter, near the southeastern margin of the field (Figure 6). From this area, total coal

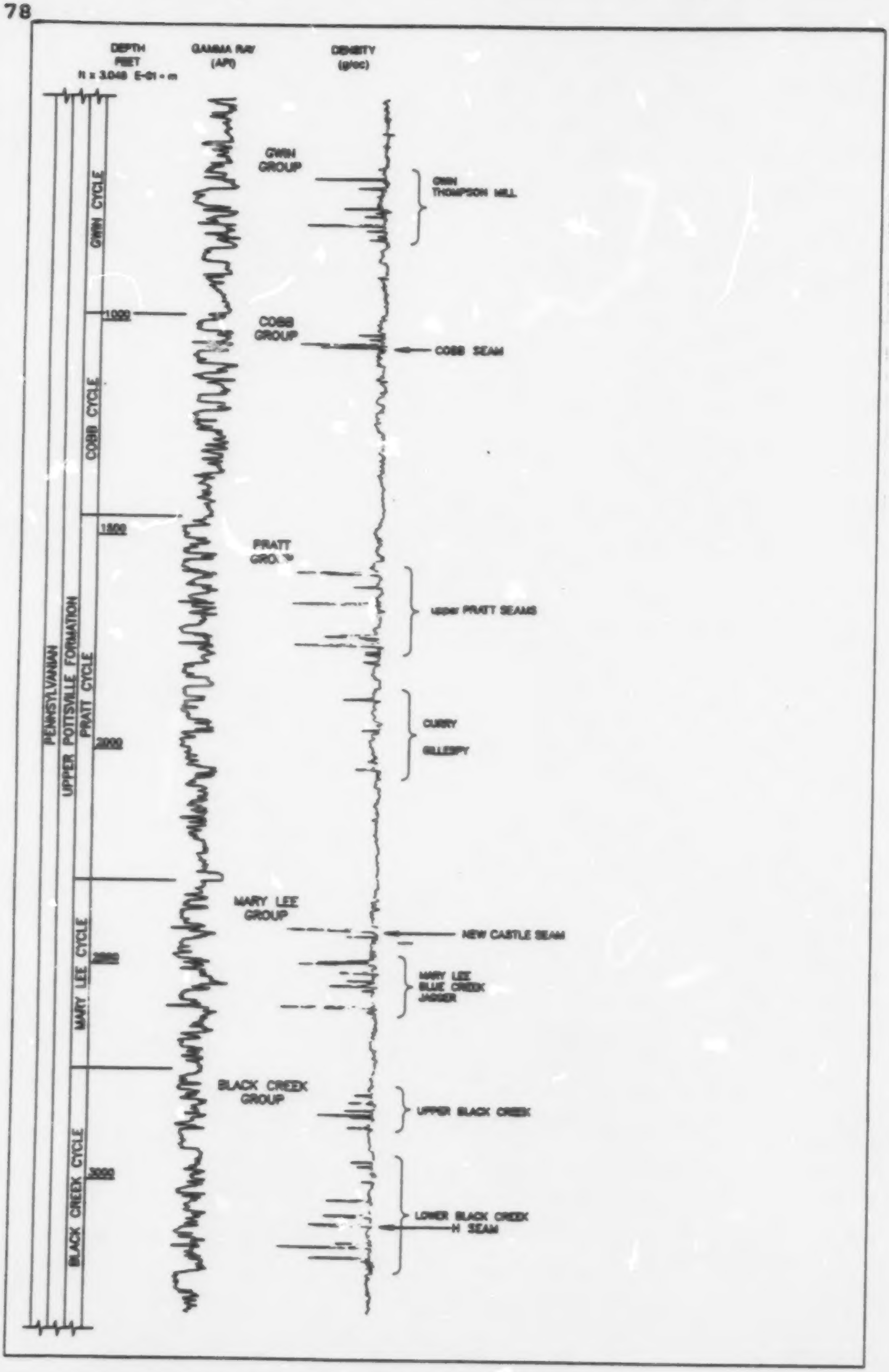

Figure 5. Typical geophysical log from the Cedar Cove field area, showing the Black Creek through Gwin coal groups.

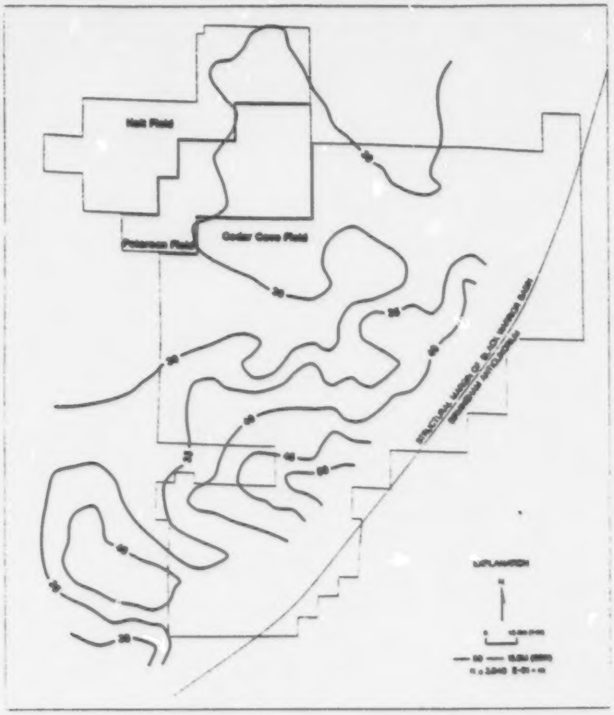
Holt Field
Cedar Cove Field
Peterson Field
EXPLANATION

Figure 6. Coal isolith map of the Black Creek through Gwin coal groups. Net coal thickness is greatest near the structural margin of the basin.

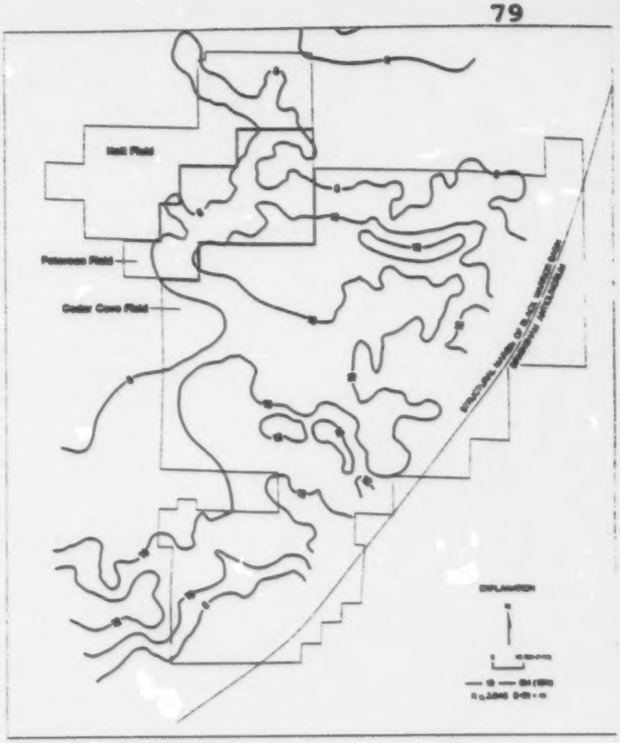
Holt Field
Peterson Field
Cedar Cove Field
EXPLANATION

Figure 7. Coal isolith map of the Mary Lee coal group. Northeast- and northwest-trending coal deposits are present.

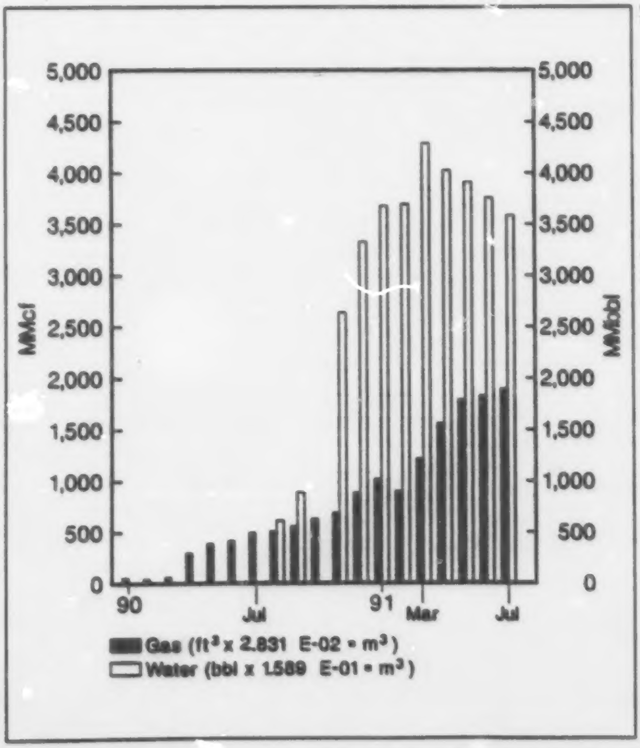

Figure 8. Monthly gas and water production in the northern Cedar Cove area.

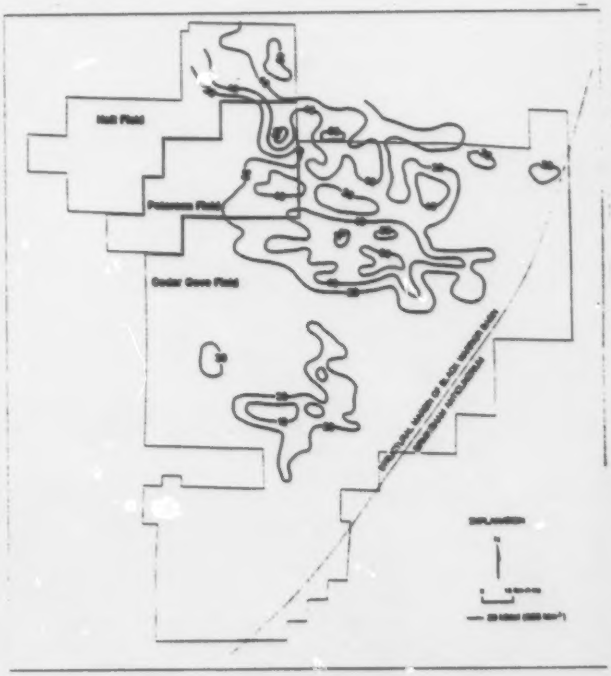
Holt Field
Peterson Field
Cedar Cove Field
EXPLANATION

Figure 9. Map of cumulative coalbed methane production in the Cedar Cove area for the first six months of sales, by well.

thickness decreases northwestward to less than 9 m (30 ft). Total coal thicknesses in individual coal groups are (1) 1.8 to 4.3 m (6.0 to 14 ft) in the Black Creek and Mary Lee, (2) 1.4 to 4.3 m (4.5 to 14 ft) in the Pratt, and (3) 0.5 to 3.0 m (1.5 to 10 ft) in the Cobb and Gwin.

Although coalbed methane wells at Cedar Cove commonly are completed in several coal groups, the Mary Lee group is the primary target owing to its regional occurrence, uniform thickness, optimum depth, and excellent gas content. Therefore, net coal thickness of the Mary Lee group was mapped separately (Figure 7). The Mary Lee cycle contains four principle coal beds: the Jagger; Blue Creek; Mary Lee; and New Castle (Figure 5). These coal beds attain maximum combined thickness near the structural margin in the southeastern part of the Cedar Cove area, where net coal thickness ranges from 2.4 to 4.2 m (8 to 14 ft) (Figure 7). In the northwestern part of the field, Mary Lee net coal thickness ranges from 1.8 to 2.4 m (6 to 8 ft).

RESERVOIR CHARACTERIZATION

The rank of Pottsville coal in the Black Warrior Basin ranges between high-volatile B bituminous and low-volatile bituminous (Telle, 1987). Generally, coal rank reflects structural configuration of the basin and is highest along the basin axis (Pashin and others, 1990). In most coal groups in the Cedar Cove area, rank is medium-volatile bituminous near the basin axis and decreases up the basin flanks to high volatile A bituminous. Ash content is 6 to 32 percent in Black Creek coal beds and 5 to 20 percent in Mary Lee coal beds. Desorbed gas contents of upper Pottsville coal beds range from 3.9 cc/g to 21.3 cc/g (125 scf/ton to 681 scf/ton).

Pressure gradients in the upper Pottsville Formation in the Warrior Basin reflect a fresh water hydrostatic gradient of 9.8 kPa/m (0.433 psi/ft), except in areas around underground coal mines. Pressure gradients near Brookwood mine in the Blue Creek bed of the Mary Lee coal group are less than 7.2 kPa/m (0.32 psi/ft) (Pashin and others, 1991). This active mine is approximately 3.2 km (2 mi) northeast of the Cedar Cove area. However, the coalbed reservoirs in the northern part of the Cedar Cove area were at, or near, hydrostatic conditions when coalbed methane production began. At Cedar Cove, bottomhole pressures range from 10 720 kPa (1 555 psi) in the Black Creek group to 1,970 kPa (200 psi) in the Gwin group.

Reservoir temperatures in the Black Warrior Basin reflect a geothermal gradient of 0.55°C/33 m (1°F/100 ft). Temperature is depth dependent; the geothermal gradient does not appear to vary across fault swarms. In the Cedar Cove area, highest temperatures occur along the basin axis in the southern part of the field, where bottomhole temperatures are 39°C (103°F) in the Black Creek group and 18°C (64°F) in the Gwin coal group.

Coal beds are the most permeable beds in the upper Pottsville Formation. Permeability of Black Creek coal beds, determined in 15 wells throughout the Cedar Cove area, ranged from 0.5 md. to 14 md. The median value of permeability-thickness (kh) was 5.5 md-m (18 md-ft). Highest permeability values were measured 3.2 to 4.8 km (2 to 3 mi) from the structural margin of the basin, where the limited data suggested a northeast-trending pattern of enhanced permeability. A nearly coincident pattern of high permeability occurs in Mary Lee coal beds. Mary Lee coalbed permeability, measured in 10 wells, ranges from 1.9 to 14 md. The median kh value for Mary Lee coal beds was approximately 12 md-m (40 md-ft). Few permeability values are available from Pratt, Cobb, or Gwin group coal beds.

Although coalbed methane production in the central part of the Cedar Cove area is commingled from the Black Creek through Cobb coal groups, half of the net coal thickness in this interval is in the Mary Lee group. Permeability calculation from pressure transient tests suggest Mary Lee and Black Creek coal beds contribute 39 and 26 percent, respectively, of the flow capacity to the wells located in the central part of the field (Sparks and Richardson, 1991).

COMPLETION PRACTICE AND PRODUCTION

COMPLETION PRACTICES

The Cedar Cove area is developed on 32-hectares (80-ac) well spacing. Conventional geological and engineering practices were modified to develop coalbed methane. The typical well is drilled to a depth of 60-m (200 ft) below the Black Creek coal group, cased with 13.97-cm (5½-inch) production casing, tubed with 7.30-cm (2⅞-inch) production tubing, and dewatered (depressurized) with a progressive cavity downhole pump driven by an electric motor.

Multiple completion involving several coal groups is standard practice throughout the area. In some cases, the Cobb and/or Gwin coal groups, were not completed. Coal groups were completed on the basis of the following criteria: (1) coal beds greater than 180 m (600 ft) deep; (2) individual coal beds greater than 0.3 m (1.0 ft) thick, and the beds are present in offset wells; (3) coal beds have a bulk density of 2.0 g/cc or less, as measured on the geophysical logs; and (4) the net thickness of the coal group exceeds 0.6 m (2.0 ft). The coal groups were individually fracture-stimulated using a cross-linked gel and 12/20 sieved size proppant sand.

PRODUCTION HISTORY

The second phase of development in the Cedar Cove area began in February 1990, with the addition of 8 wells, bringing the total to 24; monthly production from these 24 wells was 1.4 MMm^3 (50.8 MMcf) (Figure 8). Development of the area proceeded rapidly, and in July 1991, this area produced almost 53.8 MMm^3 (1.9 Bcf) of coalbed methane from 446 wells. By June 1991, cumulative methane production for the Cedar Cove Field area exceeded 558.6 MMm^3 (19.7 Bcf). In July 1991, water production from this area was 643 Mm^3 (4.06 MM bbl). Unofficial field reports for the northern area indicate gas and water production in September 1991 averaged 3.4 Mm^3/d and 55 m^3/d (122 Mcf/d and 347 bbl/d), respectively, from 407 wells.

In the Cedar Cove area, coal beds are at various stages of depressurization, because drilling occurred in stages. Although some wells may have benefitted from dewatering nearby wells (interference), appreciable production communication among wells has not been documented. Typical gas production history of a Cedar Cove coalbed methane well includes 3 stages: (1) increasing gas production to a temporary peak rate, which may occur within two to six months; (2) erratic gas production until stabilization, which may take 12 to 18 months; and (3) declining gas production for remainder of the life of the well. Generally, wells in the Cedar Cove area produce 3.7 Mm^3/d (130 Mcf/d) after three to 12 months, and individual, highly productive wells have produced at rates of 12.7 Mm^3/d to 28.3 Mm^3/d (450 Mcf/d to 1 000 Mcf/d). Initial water production rates greater than 80 m^3/d (500 bpd) are considered high; however, rates greater than 160 m^3/d (1 000 bpd) are not uncommon.

PRODUCTION TRENDS

The cumulative gas production for the first 6 months of sales should be a preliminary indicator of a well's long-term productivity. Therefore, these cumulative productions values were posted for each well, and the values were contoured (Figure 9). The most productive wells, those having 6-month cumulative production exceeding 556 Mm^3 (20 MMcf), occur primarily in the north-central and secondarily in the central part of the Cedar Cove area. In both areas, the highly productive wells occur in west- and northwest-trending patterns.

To evaluate water production we posted cumulative production for the first 6 months that each well was on pump and contoured these values (J. Ellard, unpublished map). Near the southeast margin of the basin where recharge is inferred to occur (Pashin and others, 1991), moderately high water production occurs in a pattern that parallels the basin margin. However, highest water production occurs in west-trending patterns that generally coincide with thick coal deposits in the Mary Lee group (Figure 7), which is a primary producing group for coalbed methane.

CONTROLS ON PRODUCTION

Primary control on coalbed methane occurrence and producibility is net coal thickness; west- and northwest-trending areas of high gas production (Figure 9) coincide with similar occurrences and trends of anomalously thick coal (Figures 6 and 7). The relations between gas and water production and local fracture zones are unclear. However, preliminary studies suggest that, in the above areas of highly productive coalbed methane wells, gas production is anomalously high along some fracture zones. Additional detailed geologic and engineering studies are necessary to clarify controls on coalbed methane producibility.

SUMMARY AND CONCLUSIONS

1. In the Cedar Cove area, the upper Pottsville Formation is composed several coal-bearing depositional sequences, each having multiple coal beds. The most extensive coal beds occur near the top of each sequence.

2. Net coal thickness is greatest near the structural front. Northeast-trending coal deposits parallel the structural front and the paleoshoreline, whereas northwest-trending coal deposits reflect their origin in a floodplain setting.

3. Coalbed methane wells are completed in three to five coal groups. The Black Creek and Mary Lee coal groups are the principle coalbed methane producing intervals.

4. The primary control on coalbed methane production is coalbed (reservoir) thickness; areas of high methane production coincide with areas of thick coal. Locally, anomalously high production may result from fracture-enhanced permeability, but additional studies are necessary to document these relations.

ACKNOWLEDGMENTS

P.A. Ferguson and H.A. Rush contributed geologic insights to this study. R.M. Tisdale, Linda Baker, and D.L. Burke reviewed an earlier version of this paper. Drafting and layout were by T.H. McSweeney and M.L. McAllister, and M.R. Newell assisted with manuscript preparation.

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NOTES

COALBED METHANE IN SOUTHEAST BRITISH COLUMBIA AND STRUCTURE OF THE CROWSNEST COALFIELD (FERNIE BASIN)

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The southeast British Columbia coalfields are situated in the Front Ranges of the Rocky Mountains and have been mined since the 19th century. Rock bursts, methane explosions and gas production have been a problem to the point of closing down some collieries.

The Jurassic-Cretaceous Kootenay Group contains the continental/deltaic coal-bearing sequences. The coal-bearing Mist Mountain Formation averages 500 metres in thickness with 30 to 80 metres of coal. the coal rank is between low volatile and high volatile A bituminous. The coalfields are defined by tight overturned to broad open folds complicated by thrust and normal or retrothrust faults. This study extrapolates surface data into the basins which is used to predict the CBM resource.

The coal seams expected to contain high methane contents occur at a depth between 300 metres and 2000 metres. The potentially producible CBM gas is estimated to be 10 to 13 Tcf in the Crowsnest coalfield and 7 to 8 Tcf in the Elk Valley coalfield with nominal amounts in the Flathead coalfield (less than 1 Tcf) for a total of 17 to 21 Tcf.

A detailed structural analysis of the Crowsnest Coalfield is presented with the published report described above. This interpretation, based on the geology in the report, provides a structure contour and isoburden map to the base of the coal measures. Complimenting the maps are 25 structural cross sections.

NOTES

COALBED METHANE CHARACTERISTICS OF GATES FORMATION LITHOTYPES, NORTHEASTERN BRITISH COLUMBIA

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V6T 2B4

ABSTRACT

The influence of maceral composition upon gas adsorption characteristics of medium volatile coal samples from the Gates Formation (northeastern British Columbia) was researched. Lithotype (coal facies) samples were analyzed for surface area, maceral and mineral composition and methane adsorption isotherm analysis, as well as standard coal analyses (proximate). The vitrinite of the samples analyzed ranges from 21-98% (volume %, mineral matter free); the ash yield varies from 3.61-33.83 weight %. Both maceral composition and mineral matter content play an important control in adsorption characteristics as indicated by carbon dioxide surface areas and methane adsorption isotherms. On a mineral-matter-free basis, the amount of methane adsorbed generally increases with vitrinite enrichment. Textural differences influence adsorption characteristics; methane adsorption increases with increased structured vitrinite on both a mineral matter free and raw coal basis. The lowest methane adsorption was displayed by the sample with the highest inertinite content, the fibrous (fusain) coal. Carbon dioxide surface areas of the lithotypes range from 79 - 185 m^2/g. Surface area generally decreases with increased mineral matter content, and increases with increased vitrinite content. Additionally, it was found that monolayer volumes of carbon dioxide (as calculated from the Dubinin-Radushkevich equation) are higher than those of methane (as determined from the Langmuir equation), but are correlative.

INTRODUCTION

Coal seams are compositionally heterogeneous with respect to their chemical and physical properties; such differences are known to profoundly affect the coking quality of a coal, as well as its characteristics as a source rock for liquid hydrocarbons. However, the effect of compositional variation within a seam or between different seams which serve as source and reservoir for large methane resources has not been adequately investigated. The majority of research published to date on coalbed methane in both Canada and the United States has focused on reserve estimation and reservoir characterization. Inasmuch as the primary mechanism for methane retention in coal seams is adsorption onto the internal surface, it is logical to conclude that understanding the controls on adsorption at the microscopic/molecular level will help improve resource estimations, as well as gas recovery.

In the Western Canada Sedimentary Basin, large reserves of coal are contained within Jurassic and Cretaceous sediments. These coals are believed to have generated and retained large quantities of methane (Wyman, 1984). The Cretaceous coals in particular are compositionally distinct from many of the U.S. coals. The coals are enriched in inertinite relative to vitrinite, and contain little if any liptinitic material (Kalkreuth and Leckie, 1989; Lamberson et al., 1991). As is well known, the chemistry of inertinite is distinct from that of vitrinite due to a primary oxidation phase in the peat-forming wetland. Hence, the presence of inertinite has a negative effect on the volatile matter content of a coal. Additionally, the surface properties of the two materials differ; inertinite-rich coals are more hydrophilic than vitrinite-rich coals (Arnold and Aplan, 1989).

The objective of our ongoing research is to characterize, and eventually quantify, the effect of maceral and mineral compositional variability on the methane adsorption characteristics of western Canadian coals. Reported here are the preliminary results of this research, which focuses on coals of mid-Albian age collected from the Gates Formation in northeastern British Columbia (Figure 1). The Gates Formation is correlative with the Falher Member of the Spirit River Formation, one of the major coal-bearing units of the Deep Basin gas field. Coals in the Bullmoose mine area range in reflectance ($R_o$max) from 1.02% - 1.14% (medium-volatile bituminous; Kalkreuth and Leckie, 1989).

GATES FORMATION COAL FACIES

The composition of a coal is essentially determined by a differences in hydrologic conditions and vegetation in the original peat-forming wetland together with subsequent diagenesis. These differences are expressed on the megascopic scale by variations in bright and dull layers in a coal, imparting the characteristic banded look of humic bituminous coals. Coal geologists term these distinct, recognizable layers lithotypes, which are considered to reflect coal facies. A number of classification schemes have been developed to facilitate lithotype field description. In this study, a modified Australian (Diessel, 1965) classification system was utilized (Table 1) which consists of differentiating lithotypes based on the relative percentage of bright and dull bands.

In the Gates Formation (Lamberson et al., 1991), variations in lithotype stratigraphy are interpreted to reflect variations in wetland environments ranging from herbaceous or shrubby marshes to Okefenokee-type conifer swamps (Lamberson et al., 1991). The brighter lithotypes consist primarily of vitrinite, particularly vitrinite which retains vestiges of the original cell structure (telinite, telocollinite and pseudovitrinite). From the brighter to the duller lithotypes, there is progressive increase in inertinite and in some coals, mineral matter and degraded vitrinite (desmocollinite and vitrodetrinite). This "dulling" is interpreted to reflect a change in vegetation (from woody to herbaceous) and/or changes in rate of accumulation and

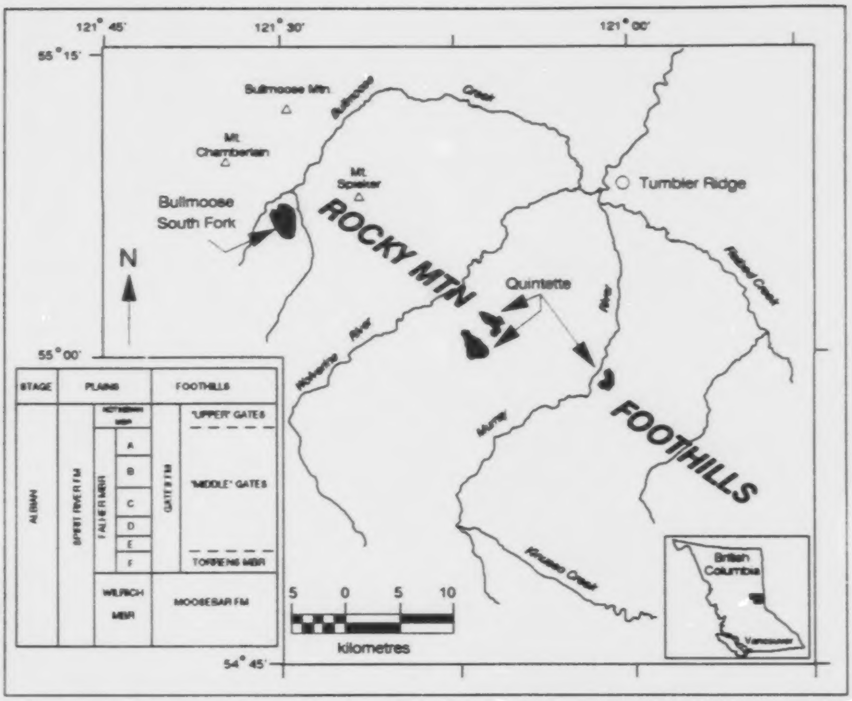
121° 45'
121° 30'
121° 00'
55° 15'
55° 00'
54° 45'
Bullmoose Mtn.
Bullmoose
Creek
Mt. Chamberlain
Mt. Spieker
Bullmoose South Fork
Tumbler Ridge
ROCKY MTN
Quintette
Flatbed Creek
River
Wolverine River
Murray
FOOTHILLS
Kinuseo Creek
N
STAGE
PLAINS
FOOTHILLS
ALBIAN
SPIRIT RIVER FM
FALHER MBR
A
B
C
D
E
F
GATES FM
'UPPER' GATES
'MIDDLE' GATES
TORRENS MBR
WILRICH MBR
MOOSEBAR FM
5
0
5
10
kilometres
British Columbia
Vancouver

Figure 1. Location map showing major coal deposits currently under, or slated for development. Inset chart shows stratigraphic nomenclature for a portion of the Lower Cretaceous in northeastern British Columbia. Map modified from Matheson (1986) and Lamberson et al. (1991). Stratigraphic chart modified from Leckie (1986), Carmichael (1988) and Lamberson et al. (1991).

Table 1. Lithotype classification scheme used in this study.
(Modified from Diessel, 1965; Marchioni, 1980 and Lamberson et al., 1991.)

Stopes-Heerlen (ICCP) Classification	Nomenclature used in this study	Description
vitrain	bright coal	subvitreous to vitreous lustre, conchoidal fracture, less than 10% dull laminae
clarain	banded bright coal	predominately bright coal, with 10-40% dull laminae
	banded coal	interbedded dull and bright coal in approximately equal proportions
	banded dull coal	predominately dull coal with 10 - 40% bright laminae
durain	dull coal	matte lustre, uneven fracture, less than 10% bright coal laminae, hard
fusain	fibrous	satin lustre, very friable, sooty to touch
no equivalent	sheared	variable lustre, disturbed bedding, numerous slip/slickenside surfaces, very brittle

decomposition of vegetal material (Lamberson et al., 1991). Fibrous coals are a special case, in that they are believed to form as a result of a fire (or a series of fires) within the wetland, and as such reflect the destruction of, rather than the presence of a particular plant community.

Although it would perhaps be ideal to analyze pure maceral separates to determine their "true" gas adsorption properties, macerals are extremely difficult to isolate from one another. Additionally, questions exist as to whether or not the chemical and physical properties of the macerals are altered by current separation techniques (see discussion in Bustin et al., in press). The natural associations of macerals (and minerals) in lithotypes provide a method by which one can study the effects of compositional variation on gas adsorption characteristics. This method of analysis requires many samples in order to quantify or statistically validate relationships. However, the general relationships may be seen by study of a suite of the lithotype samples.

METHODS

Eight lithotype samples were collected from Bullmoose mine (Figure 1). Samples were crushed to less than 250 microns for each analysis with the exception of two samples, LTC-1 and LTA1-6. These two samples were initially prepared for methane adsorption isotherm analysis to include only the 90 - 500 micron mesh fraction of the coal. The procedure was subsequently changed to crushing and wet sieving through a 250 micron screen. These two samples are currently being reanalysed. The 90-500 micron fraction of the two samples was crushed to less than 250 microns for surface area and maceral analysis. All sample were analyzed for petrography (maceral and mineral), proximate analysis, low-temperature ash, mineralogy (x-ray diffraction), sulphur, carbon dioxide surface area (25°C, low relative pressure adsorption isotherm) and methane adsorption (high pressure, 25°C methane adsorption isotherm).

Maceral, proximate and sulphur analyses were performed by standard techniques (Montgomery, 1978; Bustin et al., 1985). Maceral analyses are based on a 300 point count (mineral matter free, minerals counted separately) on a polished, 2.54 cm crushed particle pellet. Low temperature ashing of the coal samples was performed using the oxygen plasma technique described in Suhr and Gong (1983). X-ray diffraction was then used to qualitatively assess the mineral composition of each sample.

Carbon dioxide surface area analyses were performed at the University of New Mexico Center for Micro-Engineered Ceramics using a low pressure volumetric gas adsorption apparatus at 25°C. The tests were run at relative CO_2 pressures varying between approximately 0.0005 - .0100; monolayer capacities were determined from the Dubinin-Radushkevich equation (Mahajan and Walker, 1978; Sato, 1981; Lowell and Shields, 1984). Surface areas were calculated using a value of $17 \times 10^{-20} m^2$ for the cross sectional area of the carbon dioxide molecule. Methane adsorption isotherms were performed by Core Laboratories

(Calgary, Alberta) using a high pressure adsorption technique similar to that of Mavor et al. (1990), at 25°C, variable moisture content.

RESULTS

SAMPLE COMPOSITION

The relative percentage of each maceral was calculated on a volume percent, mineral matter free basis; these percentages were recalculated by the Parr formula to included mineral matter content (volume %, raw coal). Compositional data (both bases) are presented in Table 2, along with proximate and sulphur data. Maceral analysis results on a mineral matter free basis are illustrated in Figure 2. The [illegible]s analyzed are essentially a three component system consisting of vitrinite, inertinite and mineral matter. In general, the samples with a lower ash yield (LTC-1, LTC-15, LTC-7 and LTA1-6) are enriched in the structured vitrinite varieties (pseudovitrinite, vitrinite and telocollinite) with variable amounts of desmocollinite and inertinite. The higher ash yield samples (LTC-9, 11 and 14) are higher in inertinite (particularly inertodetrinite) and the more attrital form of vitrinite, i.e., vitrodetrinite (Figure 2). Sample LTC-5, the fibrous (fusain) coal, is also high in mineral matter, but is dominated by the structured inertinite varieties (fusinite and semifusinite).

The fibrous coal sample also contrasts with the remaining samples in terms of its mineralogy. LTC-5 is essentially monomineralic (Table 3), with dolomite present as pore and fracture fillings. Other examples of fibrous coal from the Gates Formation examined are characterized by the presence of carbonate in cell fillings and fractures as well (Lamberson, unpublished data). The other monomineralic sample was LTA1-6, a banded coal which has a low ash yield (3.61%) consisting predominately of quartz. The remaining samples contain dominantly quartz and kaolinite, with dolomite and ferroan dolomite occurring in minor proportions (Table 3). Quartz (silica) occurs as primary detrital grains or secondary replacements. Kaolinite (or related clay) occurs as either as primary detrital grains or concretions in the coal matrix, whereas the carbonate grains occur as concretions, cell fillings and fracture fillings.

GAS ADSORPTION

Methane adsorption isotherms are illustrated in Figure 3 on a moist, raw coal (3a) and ash-corrected basis (3b). The primary effect of the ash correction is to shift the curves upward on the graphs, without a significant shift between the curves. Although some scatter exists in the data for each isotherm, all of the isotherms have a better than 0.92 correlation (r^2)to the Langmuir equation (Mavor et al., 1990).

Table 2. Petrographic, proximate analysis and sulphur data. Expressed on several different bases.

			LTC-1 bright	LTC-15 banded coal	LTC-7 banded bright	LTA1-6 banded dull	LTC-14 dull	LTC-11 banded dull	LTC-9 dull	LTC-5 fibrous
Volume %, mineral matter free basis	Vitrinite	TELOCOLLINTE	31	31	18	12	2	5	6	1
		PSEUDOVITRINITE	13	9	6	14	0	1	0	0
		TELINITE	10	5	15	5	7	5	1	6
		VITRODETRINITE	3	8	3	0	19	21	34	2
		DESMOCOLLINITE	41	17	25	24	7	11	10	12
		STRUC VITRINITE	54	45	39	31	10	11	7	7
		DEGR VITRINITE	44	25	28	24	26	32	44	14
		TOTAL VITRINITE	98	70	67	55	36	43	51	21
	Inertinite	SEMIFUSINITE	0	11	18	19	30	29	16	13
		FUSINITE	0	13	10	10	2	4	1	58
		INERTODETRINITE	1	5	4	14	24	20	30	4
		MACRINITE	0	0	1	0	5	1	2	2
		MICRINITE	0	0	0	1	1	1	0	1
		STRUC INERTINITE	0	24	27	28	32	33	16	71
		OTHER INERTINITE	1	5	5	16	30	22	32	7
		TOTAL INERTINITE	1	29	32	44	62	55	48	78
		TOTAL LIPTINITE	0	1	0	1	2	2	1	0
TISSUE PRESERVATION INDEX			1.2	2.3	2.1	1.5	0.8	0.9	0.3	4.4
GELIFICATION INDEX			73.8	2.4	2.1	1.3	0.7	0.8	1.1	0.3
Volume %, raw coal	Vitrinite	STRUC VITRINITE	52	43	38	30	9	10	5	6
		DESMOCOLLINITE	39	16	24	24	6	10	8	10
		VITRODETRINITE	3	8	3	0	17	18	26	2
		TOTAL VITRINITE	94	66	65	54	32	38	40	19
	Inertinite	SEMIFUSINITE	0	11	17	18	27	26	12	11
		FUSINITE	0	12	9	9	2	4	1	51
		OTHER INERTINITE	1	5	5	15	27	19	25	6
		TOTAL INERTINITE	1	28	31	43	56	48	38	68
		TOTAL LIPTINITE	0	1	0	1	2	2	1	0
		ASH YIELD (MINERAL %)	4	5	4	2	10	12	22	13
Proximate		ASH YIELD (WGT %)	7.98	9.61	6.77	3.61	17.63	20.46	33.83	22.15
		MOISTURE (WGT %, AR)	1.05	0.71	0.96	0.87	0.68	0.87	0.84	0.48
		VOLATILE MATTER (DAF)	28.62	26.74	24.64	24.03	22.75	23.23	20.9	32.16
		FIXED CARBON (DAF)	71.38	73.26	75.36	75.97	77.25	76.77	79.1	67.84
SULPHUR (WGT %)			0.656	0.773	0.648	0.365	0.449	0.433	0.31	0.187

STRUC VITRINITE=structured vitrinite; telocollinite + pseudovitrinite + telinite

STRUC INERTINITE = structured inertinite; semifusinite + fusinite

DEGR VITRINITE = degraded vitrinite; desmocollinite + vitrodetrinite

AR = weight %, as received

DAF = weight %, dry ash free

WGT = weight %

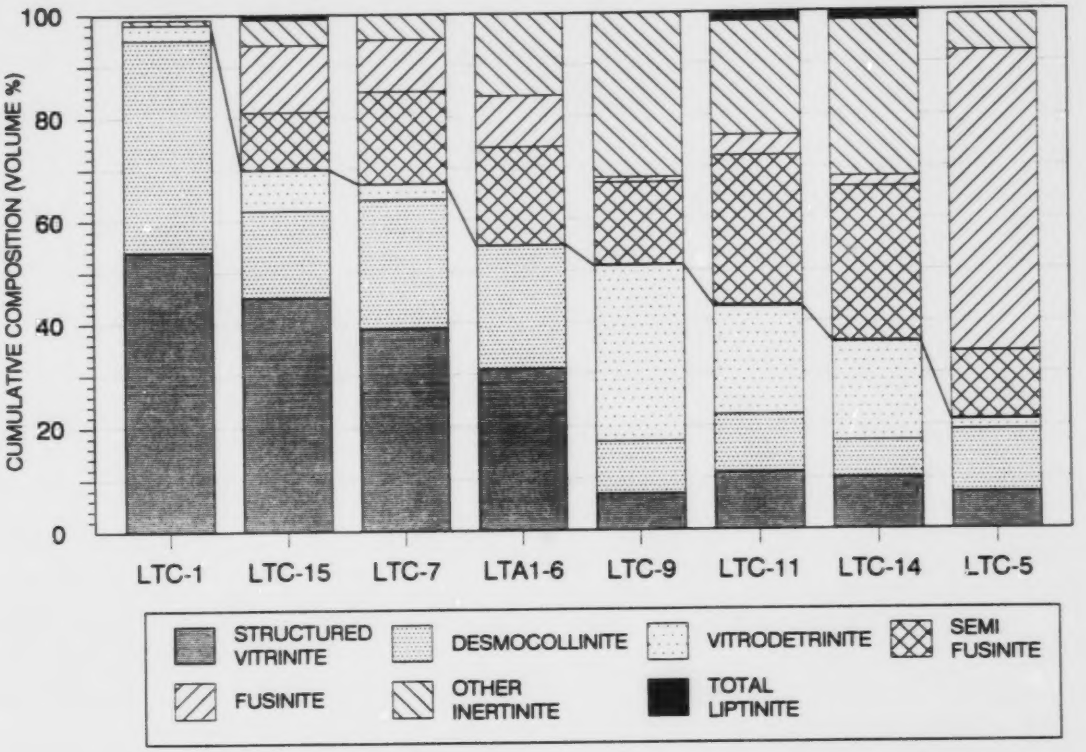

Figure 2. Maceral composition of each lithotype sample expressed on a volume %, mineral matter free basis. Dark line separates vitrinite varieties from inertinite and liptinite varieties. Data tabulated in Table 2.

Table 3. Results of qualitative x-ray diffraction (XRD) analysis of low temperature ash (LTA).

Sample	Lithotype	Low-temp. ash yield (weight %)	Quartz	Kaolinite	Dolomite	Ferroan Dolomite
LTA1-6	Banded dull	2.83	dominant	minor	-	minor
LTC-1	Bright	7.20	major	major	-	minor
LTC-5	Fibrous	33.43	minor	-	dominant	-
LTC-7	Banded bright	7.51	major	major	-	minor
LTC-9	Dull	37.59	major	minor	-	-
LTC-11	Banded dull	18.57	major	major	-	minor
LTC-14	Dull	19.15	major	minor	minor	-
LTC-15	Banded coal	11.28	major	major	minor	-

Note: detection limit of XRD technique is approximately 5%.
Dominant: essentially the only mineral present.
Major: strong peaks present (15-40%).
Minor: Weak peaks, but detectable (5-15%).

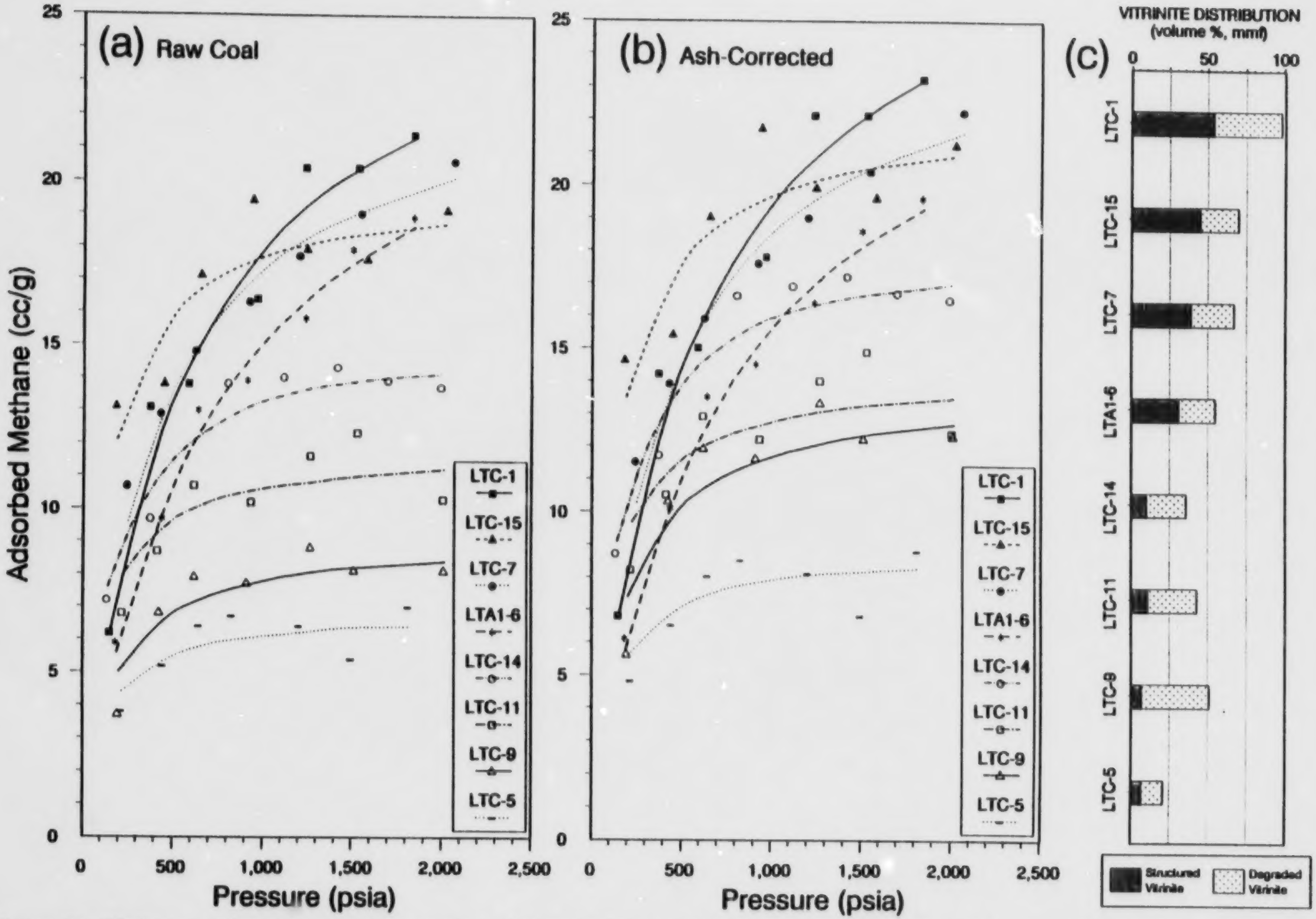

Figure 3. Methane adsorption isotherms on a (a) moist raw coal basis and a (b) moist, ash-corrected basis. Isotherm tests run at 25 degrees C. Percentage and type of vitrinite present in each sample illustrated in (c) bar graph on the right.

Table 4. Carbon dioxide surface area and gas monolayer volumes as determined by gas adsorption techniques. Both carbon dioxide and methane adsorption tests performed at 25 °C.

	Surface area [1] m sq/g	CO2 monolayer volume (cc/g)	CH4 monolayer[2] volume (cc/g)	Moisture Content [3] (%)
LTC-1	185.93	40.70	29.60	3.84
LTC-15	164.03	35.91	22.10	1.70
LTC-7	180.84	39.59	25.50	1.70
LTA1-6	187.29	41.00	26.50	5.21
LTC-14	136.25	29.83	18.20	1.40
LTC-11	139.12	30.46	14.20	1.60
LTC-9	118.22	25.88	13.70	1.50
LTC-5	79.18	17.33	8.90	1.40

1. *Carbon dioxide surface area determined at Univ. of New Mexico Centre for Micro-Engineered Ceramics.*
2. *Methane adsorption isotherms determined by Corelabs (Calgary, AB).*
3. *All equilibrium moisture values except for LTC-1 and LTA1-6.*

Carbon dioxide surface areas of the samples vary from 187.29 m^2/g to 79.18 m^2/g (Table 4); monolayer (micropore) capacities range from 17.33 cc/g to 41 cc/g (raw coal basis). These values have an experimental error of approximately +/- 10% (D. Smith, The University of New Mexico, personal communication, 1990).

DISCUSSION

A wide variation exists between samples in terms of the amount of methane adsorbed with respect to pressure. As illustrated in Figure 3c, these differences can be attributed in large part to differences in the amount of vitrinite, and, additionally, to the variety of vitrinite. Samples with a lower total vitrinite content, or a higher abundance of degraded vitrinite are found progressively lower on the pressure versus methane adsorption graph (Figure 3). As stated, the adsorption isotherms of two of the samples (LTA1-6 and LTC-1) were run at moisture contents in excess of the equilibrium moisture. It has been shown (Joubert et al., 1973) that the methane adsorption is decreased with the presence of water in the coal. However, the amount of methane adsorbed decreases to a critical saturation point, interpreted by some (Mavor et al., 1990) to be equivalent to the equilibrium moisture. After that saturation point is reached, no further decrease in adsorption is noted. Since the equilibrium moistures of the samples studied are in the range of 1.4 - 1.7 % (Table 4), it is believed that the adsorption isotherms of LTC-1 and LTA1-6 are comparable to the other isotherms obtained. However, the samples are currently being reanalysed.

Surface areas of the samples analyzed appear to be dependent on both vitrinite content and mineral matter content as illustrated in Figure 4. The relationship is not a simple one, as the lowest surface area is associated with the highest inertinite content (LTC-5, the fibrous coal sample), whereas the highest surface areas are associated with lowest ash yield. The monolayer capacities determined by the high pressure methane adsorption test are consistently lower than those obtained from the carbon dioxide low pressure isotherms (raw coal basis, Table 4). The methane and carbon dioxide monolayer capacities apparently have an exponential relationship, with a correlation coefficient of 0.95 (r^2; Figure 5). Sato (1981) also noted a relationship between the two monolayer capacities for coals of the subbituminous and bituminous coals of the San Juan Basin of the United States. Sato (1981) concluded that the difference between the two was most likely due to the molecular functionality of the two molecules. Carbon dioxide is highly polar, and may adsorb in a more tightly packed arrangement than the nonpolar methane molecule, whereas methane may be more restricted to selective sites on the surface. Further research is needed to fully understand the relationship between the methane and carbon dioxide adsorption behaviors.

CONCLUSIONS

The adsorptive capacity of a coal has been traditionally attributed to be a function of pressure (burial depth), coal rank, ash yield and moisture content (Ruppel et al., 1972; Joubert et al., 1973; Kim, 1977; Rightmire, 1984; Wyman, 1984; Choate et al., 1986). The data presented herein (Figure 3) clearly indicate that adsorptive capacity of a coal, as well as the surface area, is also a function of the maceral composition. Indeed, the variation that is seen within a single coal deposit is just as wide as that between coal ranks, as illustrated in Figure 6. As a result, a coal which has a lower rank, but is enriched in vitrinite can have a higher methane adsorption capacity than a coal which is enriched in inertinite, but is a higher rank. This observation has important implications for coalbed methane exploration. In the selection of samples for analysis, whether it be for adsorption or desorption, one must be sure that the sample is representative of the reservoir of concern. A thorough investigation into the nature of the stratigraphic and lateral facies variations should be undertaken as part of a routine exploration program.

ACKNOWLEDGMENTS

Methane adsorption analyses were conducted by Core Laboratories (Calgary, Alberta). Carbon dioxide surface areas were conducted by The University of New Mexico Center for Micro-Engineered Ceramics. The authors gratefully acknowledge Tony Ma and John Clow of Core Laboratories for their assistance and helpful discussions concerning gas adsorption techniques and data interpretation. Additionally, we would like to thank Dr. D. Smith of The University of New Mexico for his assistance and

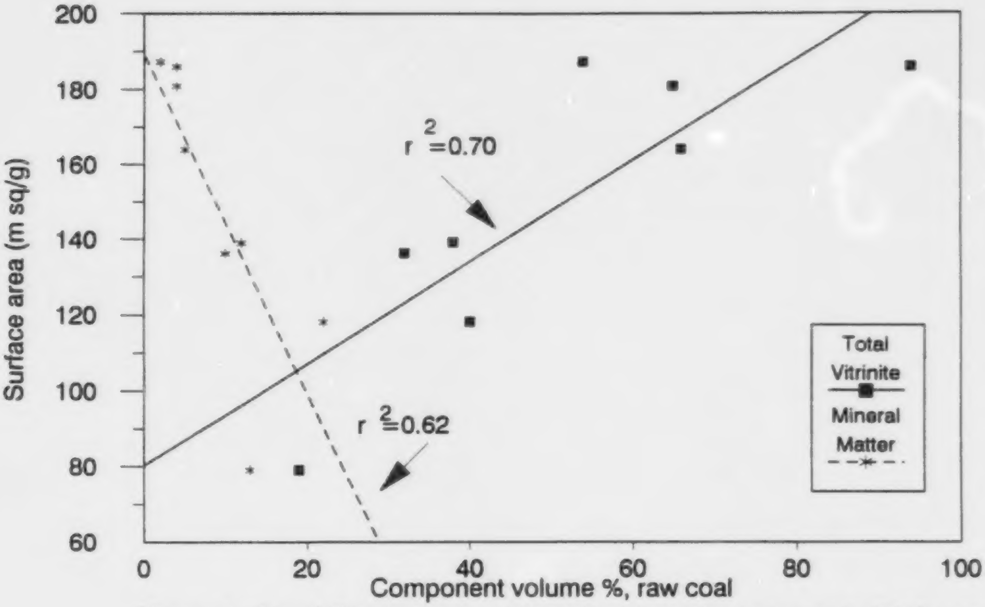

Figure 4. Correlation between carbon dioxide surface area and vitrinite and mineral matter content.

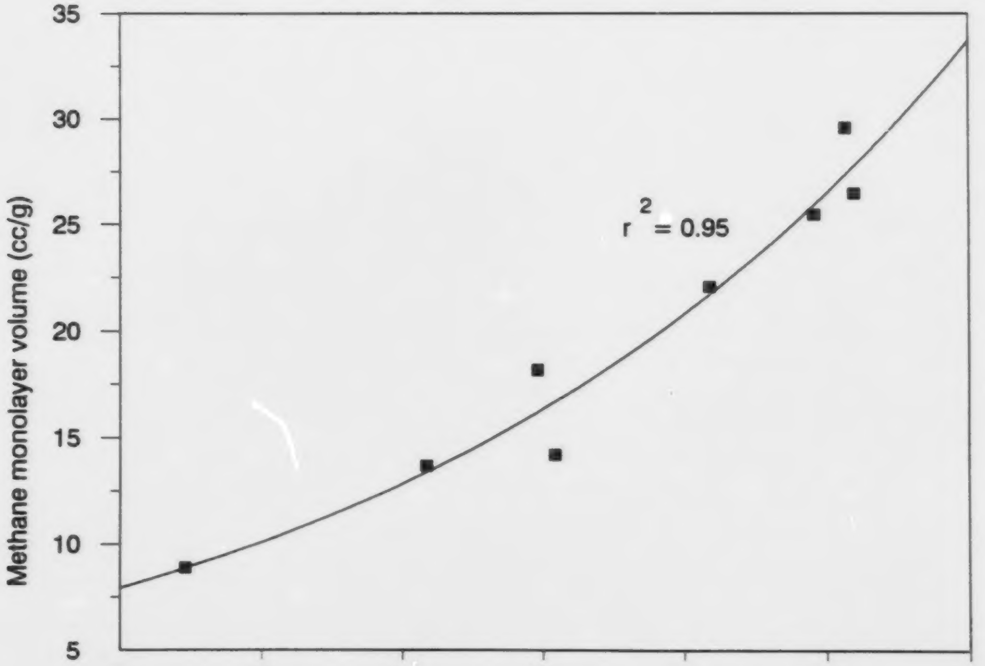

Figure 5. Relationship between carbon dioxide monolayer volumes and methane monolayer volumes as determined by gas adsorption. Methane monolayer volume determined from Langmuir equation. Carbon dioxide monolayer volume determined from Dubinin-Radushkevich equation.

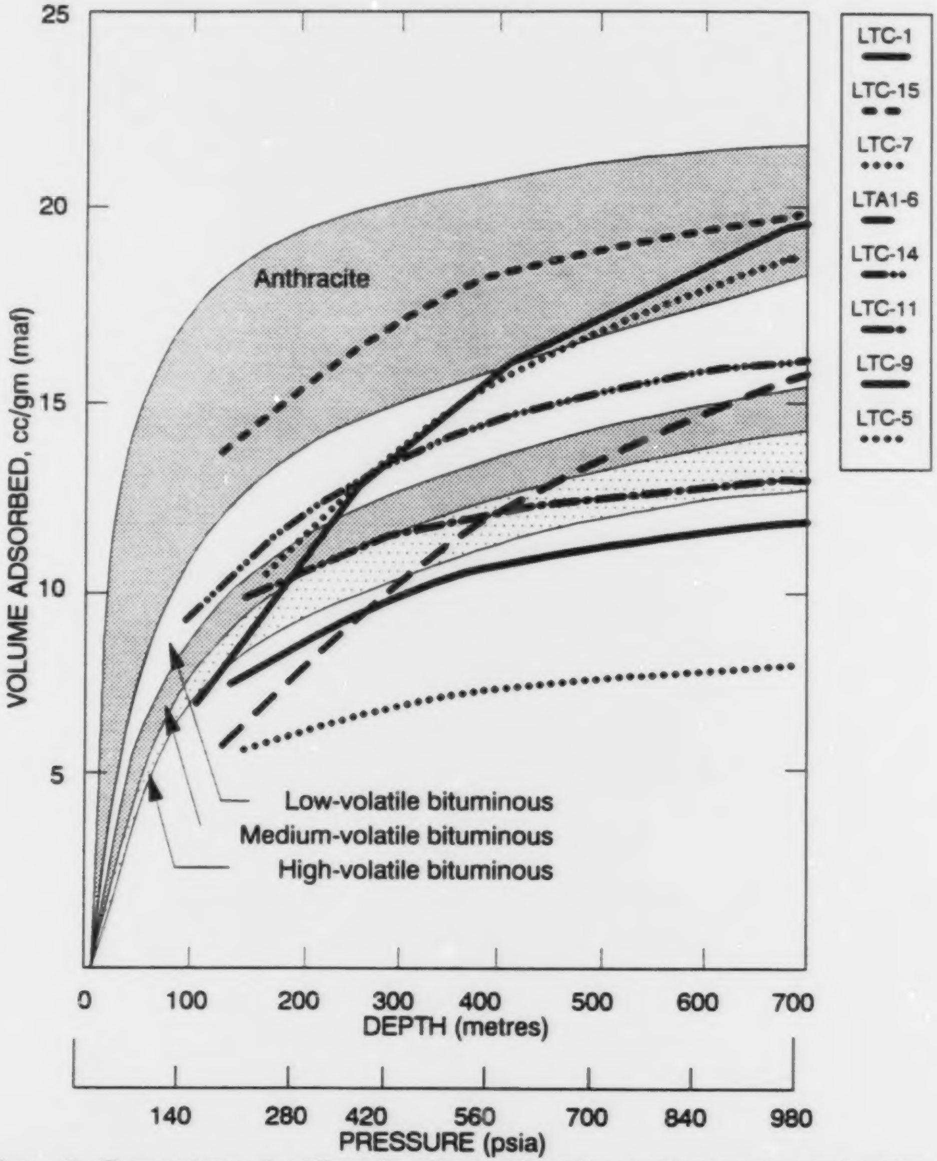

Figure 6. Comparison of portion of methane adsorption isotherms of samples with published isotherms of coals of varying ranks (rank boundaries after Kim, 1977).

helpful suggestions concerning the carbon dioxide surface area analyses. Funding for this project was provided by the Geological Survey of Canada, NSERC and the British Columbia Ministry of Energy Mines and Petroleum Resources.

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NOTES

GEOLOGY AND COALBED METHANE POTENTIAL OF THE FOOTHILLS IN THE CADOMIN AREA, ALBERTA

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ABSTRACT

Cretaceous and Tertiary strata are known from outcrop in the northeast part of the Cadomin area, while older rocks are present in the southwest and in the subsurface as known from oil and gas wells. The major structures are, from north to south: the Pedley Thrust, Coalspur Triangle Zone (formerly called Coalspur Anticline), Entrance Syncline, Mercoal Thrust, Brazeau Flats, Brazeau Thrust, Brazeau Syncline, Grave Flats Thrust, Cadomin Syncline and Nikanassin Thrust. The Pedley Thrust appears to have at least 1 km of southwest directed displacement. This fault defines the Coalspur Triangle Zone. The Mercoal Thrust may have about 2 km of southwest directed displacement and defines a triangle zone that probably formed before the Coalspur Triangle Zone. The Brazeau Thrust shows at least 3 km of northeast directed movements and places Blackstone shales on top of the Brazeau Formation. The Brazeau Syncline has an overturned southwest limb and is a tight fold. The Nikanassin Thrust forms the boundary with the Front Ranges. Three cross sections through the area were obtained by the TRIPOD Structural Geological Information System. The cross sections have been shortened by deformation in the order of 27 to 35 percent.

The economic coal seams of the Tertiary Coalspur Formation are of high volatile C rank and are present in three parallel bands in the Entrance Syncline and Coalspur Triangle Zone, where they have been mined extensively in the past. The Mercoal band is the southernmost and dips about 30 degrees to the northeast. The Coalspur band is in the middle and dips generally to the southwest. The Robb band is the northernmost band, contains northeast dipping strata and is less deformed than the Coalspur band. In the Entrance Syncline, the Coalspur coals are buried at various depths (up to 1 km) and may form exploration targets for coalbed methane. The Lower Cretaceous coals of the Luscar Group are exploited in the Cadomin-Luscar Coal field. The rank of these coals range from high volatile A to low volatile bituminous. Where buried (for example west of the town of Cadomin), they may form exploration targets for coalbed methane.

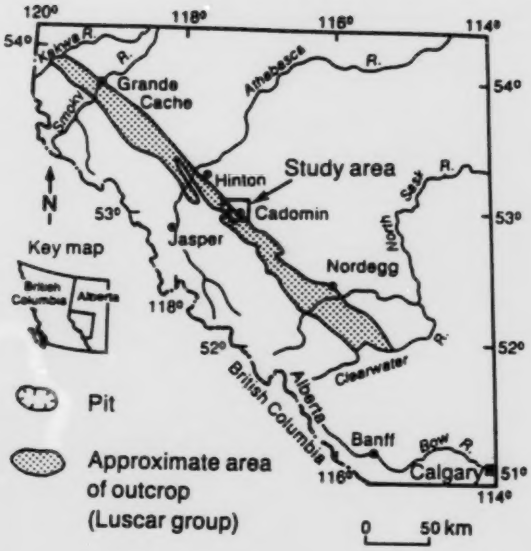
120°
118°
116°
114°
54°
Kakwa R.
Smoky R.
R.
Grande Cache
Athabasca R.
Hinton
Study area
Cadomin
N
53°
Jasper
Key map
British Columbia
Alberta
118°
Nordegg
North Sask. R.
52°
Clearwater R.
British Columbia
Alberta
Banff
Bow R.
Calgary
51°
116°
114°
Pit
Approximate area of outcrop (Luscar group)
0
50 km

Figure 1. Location of the Cadomin area.

INTRODUCTION

The Cadomin area (see figure 1 for location) contains the Cadomin-Luscar, Coalspur and McLeod River coal fields. The Cadomin-Luscar Coalfield contains two major coal mines and the Coalspur Coalfield may contain Alberta's next new coal mine. No recent geological maps exist of this area; the only available geological map is from MacKay (1929). For these reasons, the Alberta Geological Survey has mapped the Cadomin (NTS 83F/3) 1:50 000 mapsheet. Fieldwork was performed during the summers of 1989 and 1990. The area is heavily forested and consequently the exposure of bedrock is limited. The main exposures are along McLeod River, Gregg River and MacKenzie Creek. Other exposures are along roads, rail-road cuts and ridges formed by competent rock units.

Hill (1980) mapped part of the Cadomin mapsheet and the coal quality of the Cadomin-Luscar coal field was presented by Langenberg et al. (1989). In the present paper, a short introduction to the geology and coalbed methane potential of the area will be presented. The final product of this mapping project will be a 1:50 000 scale geological map and cross sections (Langenberg, in prep.).

METHODOLOGY

Information from outcrops and drill holes were collected with the TRIPOD Structural Geological Information System (Charlesworth et al., 1989). The coordinates of outcrops and drill holes are in a UTM grid (Zone 11). A geological map and cross sections were constructed with this computer system.

OUTCROPS

Information from outcrops were entered in the database. Additional outcrop information was obtained from Johnston, 1985, and unpublished coal company exploration reports.

DRILL HOLES

Information from coal exploration drill holes were entered in the database. Most of these holes were drilled by Manalta, Luscar, Denison and Crows Nest Resources (Shell).

In addition, stratigraphic picks (done by the ERCB) from oil and gas wells in this area were entered in the database.

STRATIGRAPHY

Some 4500 metres of Jurassic, Cretaceous and Tertiary strata are present in the area, overlying Paleozoic and Triassic rocks. The stratigraphic units are discussed separately from oldest to youngest.

PALEOZOIC AND TRIASSIC ROCKS

Paleozoic and Triassic rocks are known from the subsurface and from the Front Ranges above the Nikanassin Thrust.

FERNIE AND NIKANASSIN FORMATIONS

The Jurassic Fernie Formation largely consists of marine shales. The overlying, largely Jurassic Nikanassin Formation consists of marine and non-marine sandstones and shales. It is uncomformably overlain by the Cadomin Formation of the Luscar Group.

LUSCAR GROUP

The largely Albian Luscar Group consists of the Cadomin, Gladstone, Moosebar and Gates formations (Langenberg and McMechan, 1985). This group, which is equivalent to the Mannville Group of central Alberta, shows both marine and non-marine sedimentary environments and is about 600m thick.

CADOMIN FORMATION

The 10 m thick Cadomin Formation consists of chert pebble conglomerates, deposited in alluvial fans and on braided river pediment plains, and unconformably overlies the Nikanassin Formation. The Cadomin likely represents a major drop in sea level and a major sequence boundary. The Cadomin Formation is an excellent marker horizon, both at the surface and in the subsurface.

GLADSTONE FORMATION

The Lower Cretaceous (Aptian-Albian) Gladstone Formation is equivalent to the coal-bearing Gething Formation in northeastern British Columbia and the oilsands-bearing McMurray Formation in northeastern Alberta. The formation lies conformably on the Cadomin with no apparent major stratigraphic break. The section at Cadomin shows a transition from well drained alluvial plain deposits with thin coals near the base, to coastal plain deposits with thicker coals near the top; the section is 125 metres thick.

MOOSEBAR FORMATION

The Moosebar consists of marine shales and sandstones and is about 75 metres thick. Several marine cycles can be recognized in the Albian Moosebar/lower Gates succession (Macdonald et al., 1988).

The lower Moosebar Formation consists of a series of shales interbedded with sharp based siltstones and thin sandstones. It is interpreted to have formed in an offshore environment in which storm events periodically deposited thin sand units.

In the upper Moosebar more sandstones (often with hummocky cross stratification) are found. The hummocky cross stratification supports the storm deposited origin and has been found in other locations of the Moosebar to Gates transition. A glauconitic, sharp based pebble conglomerate bed is found in the upper Moosebar and is interpreted as an offshore transgressive deposit. It may in part represent very slow deposition of a condensed section. The boundary between Moosebar and Gates is gradational in a coarsening-up succession.

GATES FORMATION

The Albian Gates Formation consists of the Torrens, Grande Cache and Mountain Park members and is about 400 metres thick. Both shallow marine and non-marine sedimentary environments are present.

Torrens Member

The offshore/transgressive deposits of the Moosebar give way upsection to lower shoreface and finally foreshore sediments of the Torrens Member. The trace fossil assemblage is consistent with this interpretation.

The Torrens member consists of massive (though occasionally thinly bedded), fine to very fine grained sandstone. Faint parallel laminations are the predominant structures, with some trough cross bedding and hummocky cross stratification also present. Scour surfaces, with pebble lag deposits, are also common in the unit. Mudstone is a minor lithology in this cycle and is usually associated with the hummocky cross stratification. Trace fossils may be present. The Torrens is interpreted to be a succession of prograding shoreline deposits, with upper shoreface to foreshore environment transitions being present.

Grande Cache member

The base of the Grande Cache Member in the Cadomin area is the 10 m thick Jewel seam. Additional coal seams are present higher in the section (such as the R seam, stratigraphically 60 m above the Jewel seam). However, these coal seams are generally uneconomic in the near surface of the Cadomin area. The low-lying Okefenokee Swamp, which is some distance from active shoreline processes, might be a modern day model for these Cretaceous coals.

The sandstones of the lower part of the Grande Cache Member are often brackish until the first major fluvial sandstones are encountered. A brackish water interpretation is based on the presence of trace fossils and the presence of lenticular bedding throughout this interval. Specimens of the siliceous foraminifera *Hippocrepina (?) sp.*, *Miliammina (?) sp.* and *Saccammina sp.* have been recovered from three locations above the Jewel seam in the Cadomin area and are indicative of a shallow brackish (not normal marine) marine environment (John Wall, pers. comm.). The upper part of the Grande Cache member is largely non-marine and contains fining-upward sequences.

Mountain Park Member

The base of the Mountain Park Member is generally defined at the base of the first major greenish colored sandstone encountered going upsection from the major coal seams. These sandstones are interpreted to be large scale fluvial deposits and may occur at various stratigraphic levels, making this field mapping criteria somewhat arbitrary if only limited exposure is available.

The contact between the Mountain Park Member and the overlying dark grey shales of the Blackstone Formation is generally sharp.

BLACKSTONE FORMATION

The formation consists largely of dark marine shale and siltstone, with minor beds of sandstone, bentonite and some ironstone concretions. Some 500 m of Blackstone sediments may be present in the hanging wall of the Brazeau Thrust (figure 3), although there may be structural repeats present. Its age is late Albian to late Turonian. Stott (1963) distinguishes 4 members in this formation, but they are not easily mappable in this poorly exposed area.

CARDIUM FORMATION

The Cardium Formation consists of marine sandstone, siltstones and shale. It forms a useful marker horizon for mapping purposes, because it is relatively thin (about 80 m) and the sandstones forms ridges, that are easy recognizable on the aerial photographs. The marine sandstones often contain hummocky cross beds and trace fossils. The Blackstone and Cardium formations form a coarsening upwards succession, indicative of a fall in relative sea-level.

Four members can be recognized in outcrop (Stott, 1963), but are too thin to be mappable on a 1:50 000 scale. The age of the formation is late Turonian to early Coniacian.

WAPIABI FORMATION

The Wapiabi Formation includes all the beds between the Cardium Formation and the greenish sandstones of the Brazeau Formation and is about 600 m thick. The age of the formation is Turonian to Campanian. Stott(1963) distinguishes 7 members in the Wapiabi Formation. However, the only easily mappable unit on a 1:50 000 scale is formed by the marine sandstones of the Chungo Member. For this reason the Wapiabi Formation is divided into the Upper and Lower Wapiabi members, whereby the base of the Chungo Member is used as marker horizon.

Lower Wapiabi members

The lower members are the Muskiki, Marshybank, Dowling, Thistle and Hanson members, which are dark grey, marine shales and siltstones. The Marshybank Member contains a larger percentage of siltstones and the Thistle Member consists of calcareous shales (Stott, 1963), but these members could not be mapped separately.

Upper Wapiabi members

The upper members are the Chungo and Nomad members. The Chungo consists of about 70 metres of fine grained, often reddish-brown weathering sandstones and minor siltstone. Hummocky cross-stratification and trace fossils, such as *Planolites* sp. and *Skolithos* sp., indicate that these sandstones are largely marine and clearly distinctive from the younger alluvial sandstones of the Brazeau, Coalspur and Paskapoo formations. Marine bivalves can be found in the Chungo sandstones.

The Nomad Member consists of dark grey marine shales in between the Chungo sandstones and the greenish sandstones of the Brazeau Formation. This member is about 30 metres thick.

BRAZEAU FORMATION

The Brazeau Formation, together with the Coalspur and Paskapoo formations forms part of the Saunders Group (Jerzykiewicz, 1985). The Brazeau Formation consists of about 1200 metres of sandstones, shales and some coal seams above the marine shales of the Wabiabi Formation and below the basal Entrance Conglomerate of the Coalspur Formation. Some exploration for coal in the Brazeau Formation has been performed by Luscar and Crows Nest Resources. Up to 4 metres of coal has been reported in their drilling programs.

COALSPUR FORMATION

The Coalspur Formation (Jerzykiewicz, 1985) contains a 600 metres thick continental succession of interbedded sandstones, mudstones and thick economic coal seams. The base of the Coalspur Formation is the so-called Entrance Conglomerate. Thick coal seams interbedded with coaly shales and numerous bentonites occur in the upper part of the formation. This interval is known as the Coalspur coal zone. The Val d'Or coal seam is at the top of the interval and the Mynheer coal seam is at the bottom. These seams (plus other coal seams) are recognizable in the whole area between Hinton and Coal Valley. The Cretaceous-Tertiary boundary is at the base of the Mynheer coal seam (Jerzykiewicz and Sweet, 1986). The Coalspur Formation represents a nonmarine, fluvially dominated environment of deposition.

PASKAPOO FORMATION

The Paskapoo Formation consists of at least 1000 metres thick alluvial sandstones and mudstones above the uppermost coal seam of the Coalspur Formation, which is the Val d'Or Seam in the Cadomin area.

STRUCTURAL GEOLOGY

The major structures of this foothills area are, from north to south the Pedley Thrust and Coalspur Triangle Zone (formerly called Coalspur Anticline), Entrance Syncline, Mercoal Thrust, Brazeau Flats, Brazeau Thrust, Brazeau Syncline, Grave Flats Thrust, Cadomin Syncline and Nikanassin Thrust. These structures are shown in the maps of figures 2 and 3. The down-plunge cross section BB" is shown in figures 4 and 5.

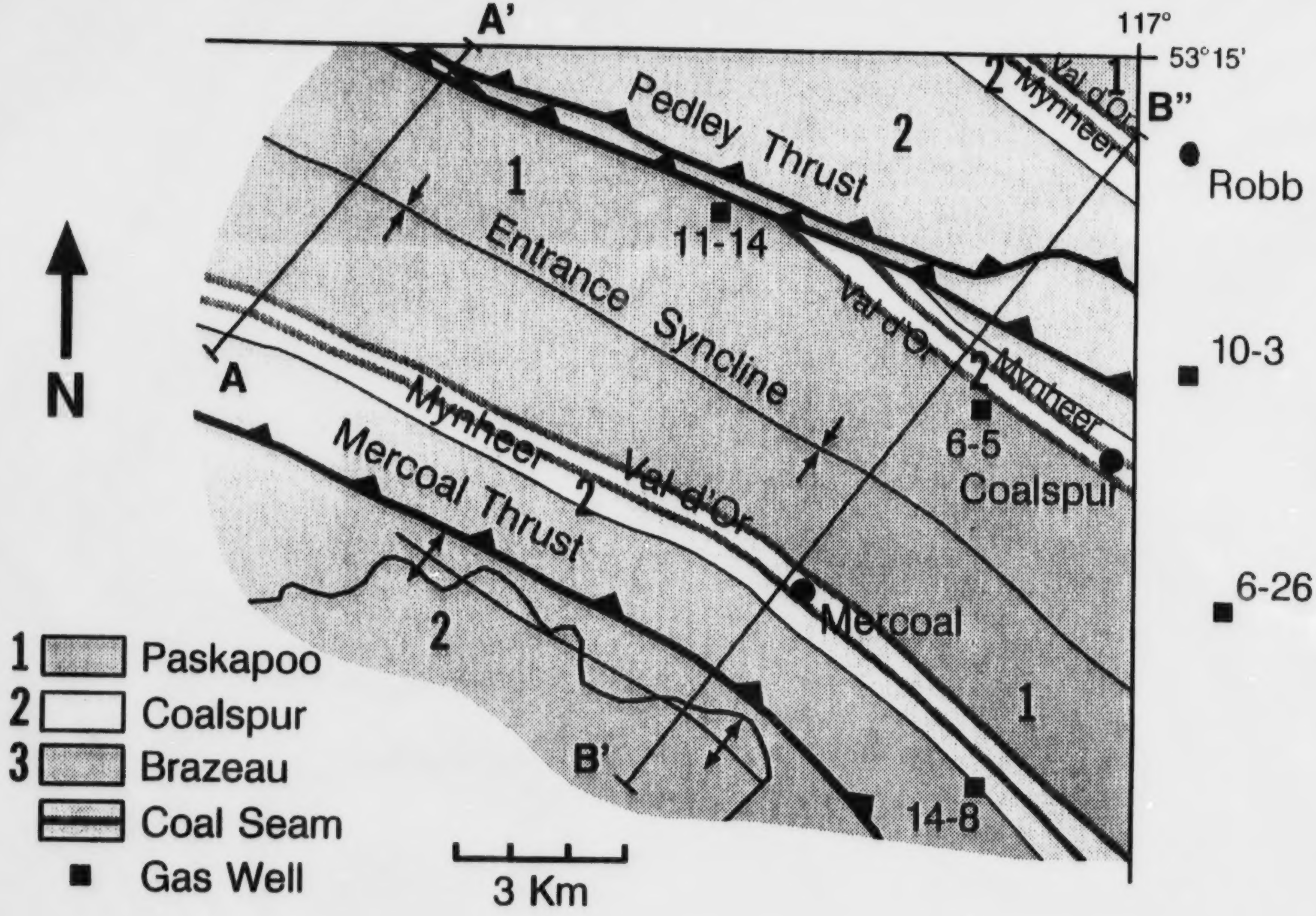
A'
A
B"
B'
117°
53°15'
N
Pedley Thrust
Entrance Syncline
Mercoal Thrust
Val d'Or
Mynheer
1
2
11-14
6-5
10-3
6-26
14-8
Robb
Coalspur
Mercoal
1 Paskapoo
2 Coalspur
3 Brazeau
Coal Seam
Gas Well
3 Km

Figure 2. Geological map of part of the northern half of the Cadomin Mapsheet.

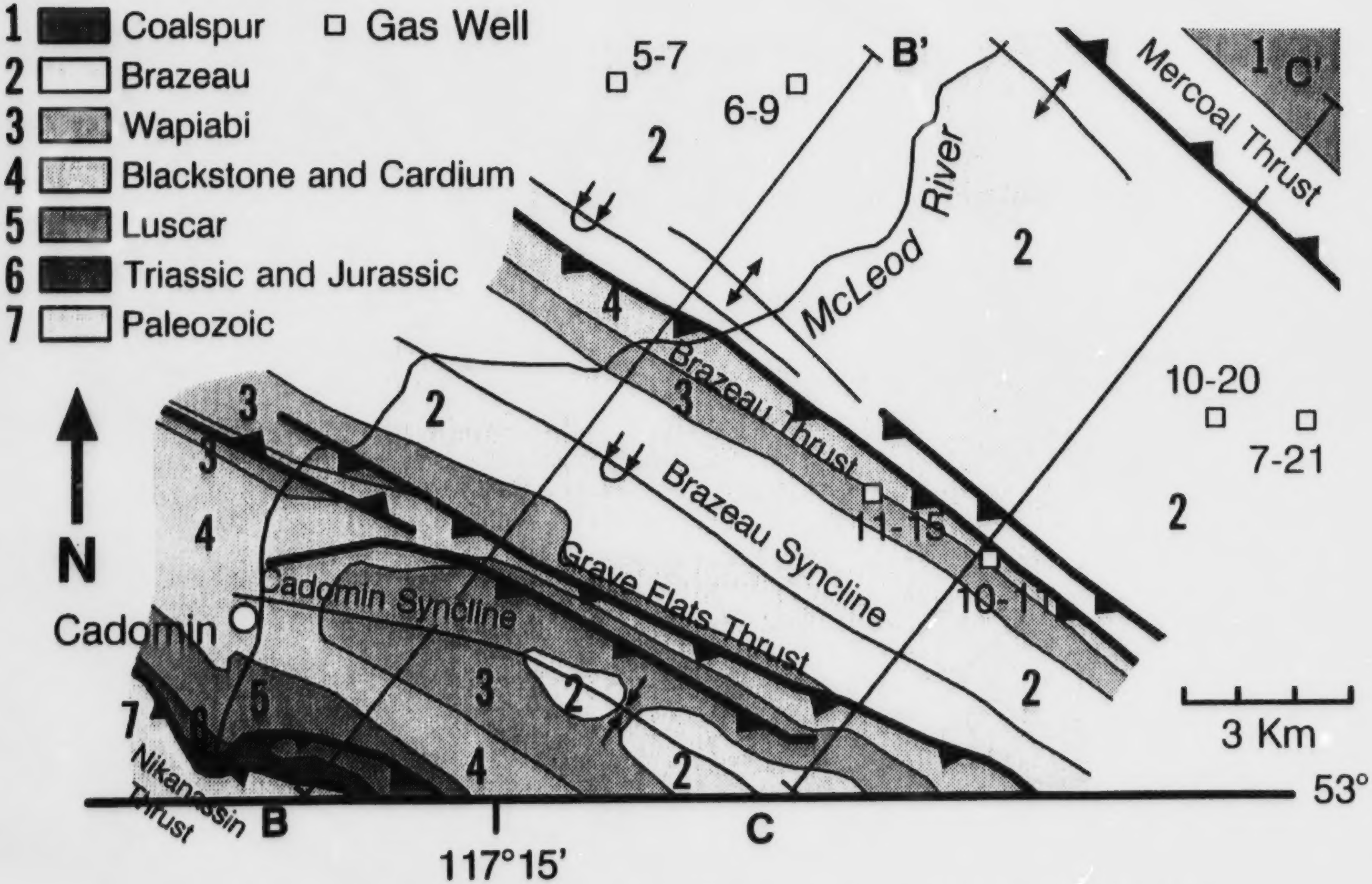
1 Coalspur
2 Brazeau
3 Wapiabi
4 Blackstone and Cardium
5 Luscar
6 Triassic and Jurassic
7 Paleozoic
□ Gas Well
N
5-7
6-9
10-20
7-21
11-15
10-11
B'
C'
B
C
McLeod River
Mercoal Thrust
Brazeau Thrust
Brazeau Syncline
Grave Flats Thrust
Cadomin Syncline
Nikanassin Thrust
Cadomin
3 Km
53°
117°15'

Figure 3. Geological map of part of the southern half of the Cadomin Mapsheet.

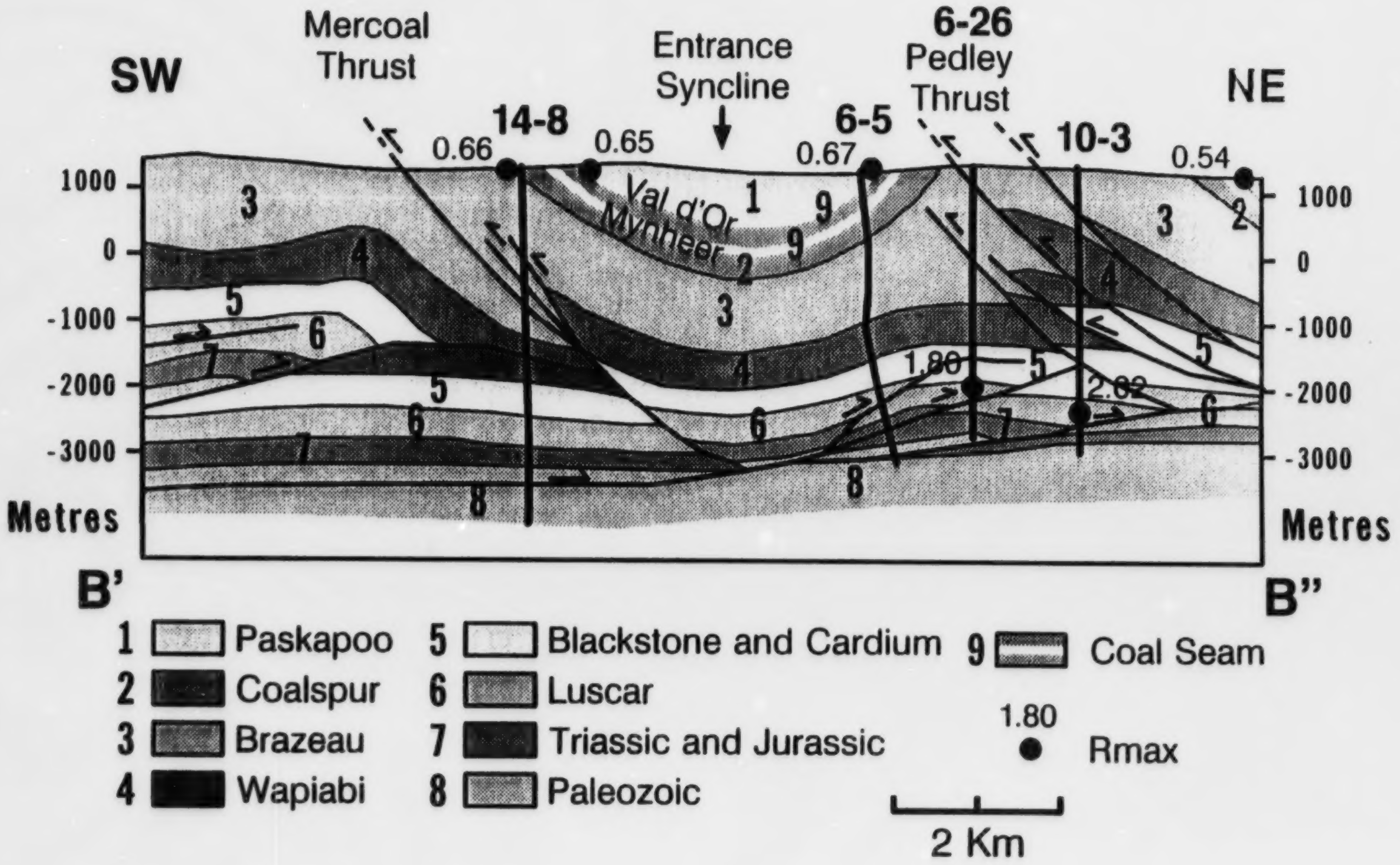
SW
Mercoal Thrust
14-8
0.66
0.65
Entrance Syncline
Val d'Or
Mynheer
6-5
0.67
6-26
Pedley Thrust
10-3
0.54
NE
1.80
2.02
1000
0
-1000
-2000
-3000
Metres
B'
B"
1 Paskapoo
2 Coalspur
3 Brazeau
4 Wapiabi
5 Blackstone and Cardium
6 Luscar
7 Triassic and Jurassic
8 Paleozoic
9 Coal Seam
1.80 Rmax
2 Km

Figure 4. Cross section B'B" through the northern half of the Cadomin Mapsheet.

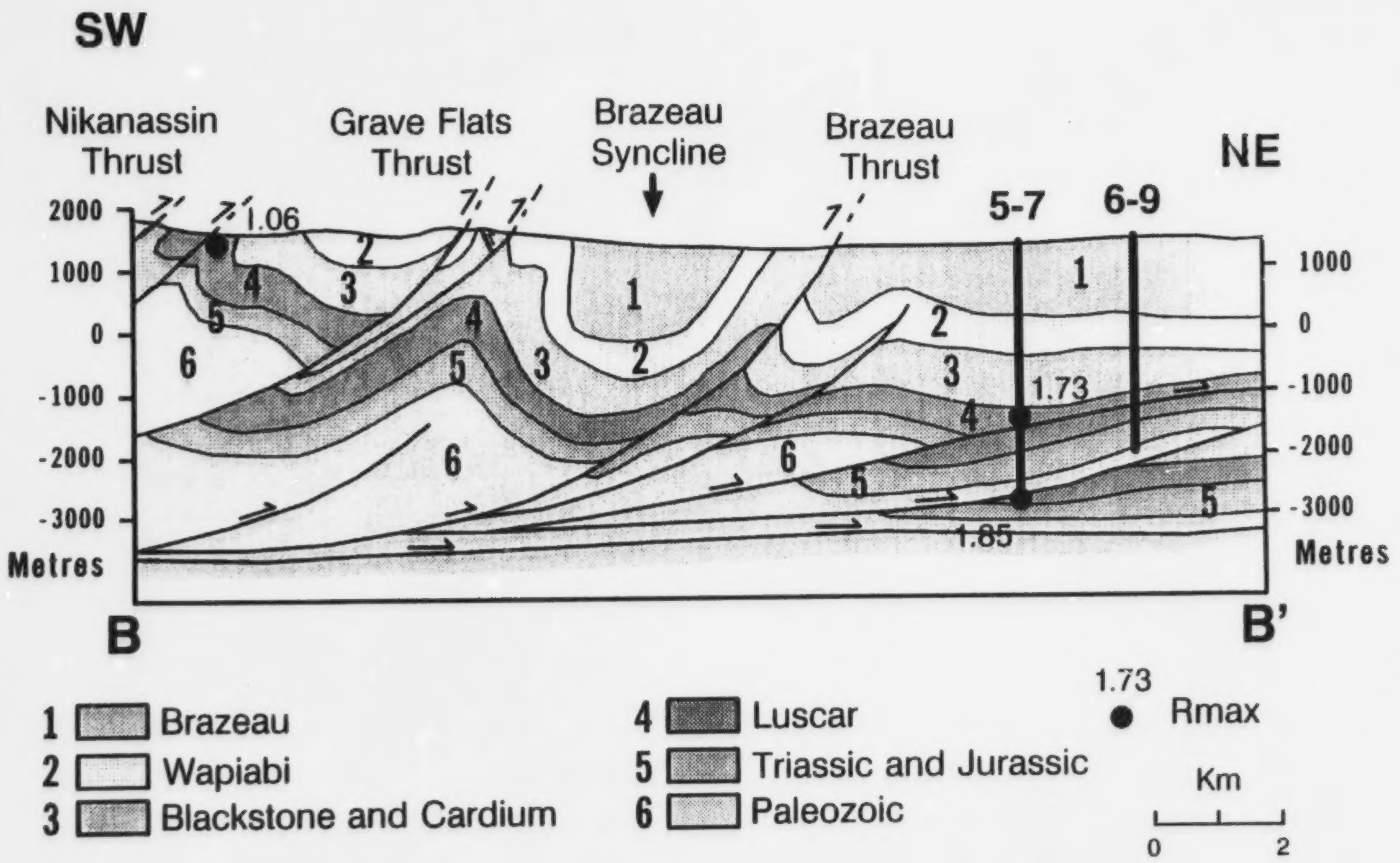
SW
NE
Nikanassin Thrust
Grave Flats Thrust
Brazeau Syncline
Brazeau Thrust
5-7
6-9
1.06
1.73
1.85
1
2
3
4
5
6
2000
1000
0
-1000
-2000
-3000
Metres
B
B'
1 Brazeau
2 Wapiabi
3 Blackstone and Cardium
4 Luscar
5 Triassic and Jurassic
6 Paleozoic
1.73 ● Rmax
Km
0
2

Figure 5. Cross section BB' through the southern half of the Cadomin Mapsheet.

The Pedley Thrust appears to have at least 1 km of southwest directed displacement. This fault defines the Coalspur Triangle Zone. The Mercoal Thrust may have about 2 km of southwest directed displacement and defines a triangle zone that formed earlier than the Coalspur Triangle Zone, as shown by cut-off relationships. The Brazeau Thrust shows at least 3 km of northeast directed movement and places Blackstone shales on top of the Brazeau Formation. The Brazeau Syncline has an overturned southwest limb and is a tight fold. The Nikanassin Thrust forms the boundary with the Front Ranges. The cross sections have been shortened by deformation in the order of 27 to 35 percent.

COAL RESOURCES

The economic coal seams of the Coalspur Formation are present in the area in three parallel bands in the Entrance Syncline and Coalspur Triangle Zone. The Mercoal band is the southernmost, contains the Mercoal Project of Manalta, and dips about 30 degrees to the northeast. The Coalspur band is in the middle, contains the structurally thickened Coal Valley pod east of the map area and dips generally to the southwest. The Robb band is the northernmost band, contains northeast dipping strata and is less deformed than the Coalspur band.

The Lower Cretaceous coals of the Luscar Group are exploited in the Cadomin-Luscar Coal field in the Cardinal River Mine (annual production in 1989 of 3 million tonnes of raw coal) and Gregg River Mine (annual production in 1989 of 2.6 million tonnes of raw coal). The Jewel seam is the major economic coal seam and is about 10 m thick.

COALBED METHANE POTENTIAL

In the Entrance Syncline, the Coalspur coals are buried at various depths (up to 1 km), are of high-volatile bituminous rank and may form exploration targets for coalbed methane.

The rank of the Jewel seam of the Luscar Group ranges from high volatile A to low volatile bituminous (Langenberg et al., 1989). The cross section of figure 5 shows the Jewel seam at varying depth along the Cadomin Syncline, but generally in the range of 100 to 1000 metres deep in the area west of Cadomin. The general plunge of the fold axes is 10 degrees to the southeast, and the Jewel seam is probably at larger depths than 1000 metres in the eastern part of the Cadomin Syncline along the McLeod River. It can be concluded that, in the general area west of the town of Cadomin, there is an area of at least 20 km^2 underlain by the 10 meter thick Jewel seam of high- to medium-volatile bituminous rank. This includes areas that contain structurally thickened coal according to surface exposure to the west of this area. Consequently, this area contains a coal reservoir with a volume of 2 x 10^8 m^3 and (based on an average density of 1.2 for this type of coal) a mass of 2.4 x 10^8 tonnes (2.64 x 10^8 tons).

One can assume an average gas content for coals of this rank of 13 cm^3/g (Levine, 1990). Therefore, the small area west of Cadomin could contain 3.1 x 10^9 m^3 (about 100 BCF) of methane. This resource is comparable in size to well-known gas fields such as Findley, Basing, and Mountain (ERCB, 1989). The area further west contains additional coalbed methane resources, but a number of thrust faults disrupt the continuity of the reservoir.

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A METHOD OF FRACTURE ANALYSIS TO OPTIMIZE COALBED METHANE PRODUCTION

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Conventional remote sensing, when used exclusively, inadequately defines underground fracture systems for coalbed methane. A method which combines structural analysis, joint mapping and interpretation of remote sensing data effectively defines zones of higher fracture intensity. Identification of these zones allows optimal location and spacing of coalbed methane wells and correct interpretation of production trends.

A system has been developed to consistently define linear features and joint patterns. This mapping program classifies the strike, development, dip and spacing of joints observed in the field. joints are then grouped into categories based on joint plane development. Data on faults, folds and coal cleat are also recorded. The intent of this joint classification system is to record consistent, reproducible data. These data are then entered into a computer to generate fracture maps and rose diagrams. This method allows evaluation of large areas, as well as defining detailed structures within a specific area.

The linear study consists of interpreting and classifying linears from a variety of remote sensing imagery, including low and high altitude photos, SLAR and thematic mapper. The resulting fracture analysis incorporates data from the joint field mapping program and the linear study. Data on regional and local structures are also evaluated, as folds, flexures and faults directly affect production.

Detailed study of production trends vs. fracture zones in the Oak Grove degas field of Alabama confirmed the importance of structure; wells connected to fracture systems yielded higher production. Although data obtained from this study established the existence of subsurface communication between seams via fracture systems, extensive field mapping reveals fracture avenues from subsurface coal seams to the surface. The evidence for this is continuous stream bubbles observed in creek beds.

Knowledge of local structure optimizes well spacing, increases methane production and minimizes cost. Although well spacing of 40 to 160 acres are commonly used in degas fields, optimum grid spacing for an individual field is highly dependent on fracture patterns. Fracture zones greatly increase the communication between wells horizontally and between seams vertically. Increased well spacing in highly fractured areas does not decrease early production, yielding a longer production period. Several large-scale degasification projects have successfully used this combined method of joint mapping, linear study and structural analysis to optimize well placement and spacing, thus optimizing gas production.

NOTES

EVALUATION OF COALBED NATURAL GAS OPEN HOLE CAVITY COMPLETION PRODUCTIVITY

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ABSTRACT

San Juan Basin, Fruitland Formation coalbed natural gas wells completed with open hole cavities using a controlled injection-blowout technique are often producing significantly greater gas and water rates than cased, hydraulically fractured wells in similar geologic environments. This paper discusses the evaluation of two open hole cavity wells at Gas Research Institute (GRI) research sites in Colorado. The purpose of this research was to collect and interpret data required to determine the reasons for the greater productivity of cavity well completions relative to cased, fractured well completions.

The cavity completion effectively connects the coal natural fracture system and the well. At the Completion Optimization and Assessment Laboratory (COAL) Site, the pre-cavitation fluid productivity appeared to be controlled by the lower permeability butt cleat system. Post-cavitation productivity appears to be controlled by the greater permeability face cleat system. The 13 fold increase in gas productivity at the Site caused by the cavitation process is due to increased well-reservoir connectivity. The presence of the cavity is responsible only for a 60% increase in productivity.

At the Vertical COAL Site that was designed to study multi-layered coal reservoir productivity, an upper coal interval was in effective communication with the wellbore prior to cavitation. As a result, the cavitation process did not increase the productivity of the upper gas producing interval even though a cavity of significant volume was created. The productivity of deeper water producing intervals was improved.

The cavity wells outperform cased, fractured wells since the productivity of offset cased, cross-linked gel, high proppant concentration, fractured wells is believed to be dominated by the lower butt cleat permeability. Recent evidence suggests that cross-linked polymers cause formation damage. Not all fractured wells are poor producers.

CAVITY WELL COMPLETION BACKGROUND

The Fruitland coalbed gas well openhole cavity completion technique was pioneered by Meridian Oil Company in 1987.[1] After production data for several new Meridian cavity wells became available in the public domain, many operators with Fruitland coal acreage in the San Juan Basin became interested in the cavity technique. Wells completed with cavities are often, but not always, outperforming adjacent wells completed by running and cementing casing followed by perforation and hydraulic fracture stimulation. The stimulation of cased wells has been required in an attempt to effectively connect the coal reservoir and the wellbore and to bypass damage to near wellbore permeability.

The Fruitland coalbed gas well cavity completion technique has since been successfully applied by several operators in addition to Meridian[2,3,4,5] in the high volatile A bituminous and greater rank area[6] of the northern San Juan Basin located in Southwest Colorado and northwestern New Mexico. For example, Devon Energy Corporation has applied the cavity completion technology very successfully in the Northeast Blanco Unit that is located in San Juan and Rio Arriba counties of New Mexico.[7] Devon's original plans called for completing wells with cased, hydraulic fracture technology as well as with cavity techniques. Based upon the initial gas and water productivity of the cavity wells, the original ten cased, fractured wells were replaced with new wells completed with cavities.[8] These new wells were located within 100 meters of the twinned, original cased, fractured well location.

Table 1 compares initial test production rates of the original cased, fractured wells with the initial and longer term cavity well gas rates. The initial gas production rates of the cavity completions were approximately 21 times the initial gas production rates of the cased, fractured wells. The ratio between the stabilized cavity well gas production rates and the cased, fractured well initial gas rates was 6.7. The 400R well has not been connected to sales lines as yet. This disparity in Fruitland coal well initial and long term gas production rates from the two completion types can be illustrated with other examples from the Cedar Hill, Meridian 400, and portions of the northern Ignacio Blanco Field, all of which are in the northern San Juan Basin.

Table 1. Northeast Blanco Unit Completion Productivity

Originally Cased & Fractured Wells		Re-Drilled Cavity Wells			Cavity/Cased Production Ratio
Well Number	Initial Gas Rate	Well Number	Initial Gas Rate	Stable Gas Rate	Initial/Initial
	m^3/D		m^3/D	m^3/D	-
400	3,100	400R	73,600	?	23.6
403	28,000	403R	309,000	147,000	10.9
404	4,200	404R	640,000	184,000	150.0
413	11,000	413R	306,000	93,400	27.8
421	23,000	421R	648,000	184,000	28.6
423	6,800	423R	283,000	119,000	41.7
425	7,900	425R	374,000	76,500	101.7
427	24,000	427R	252,000	56,600	10.3
429	13,000	429R	56,600	25,500	4.3
441	20,000	441R	19,800	14,200	1.0
Total	142,000	Total	2,962,000		20.8

Openhole cavity wells are installed using a controlled blowout technique in the following manner:

1. Drill to within several meters of the top of the coal interval of interest using a conventional rotary drilling rig.
2. Cement production casing to surface. Release the drilling rig.
3. Rig up a modified completion rig capable of controlling coal reservoir pressures with blow-out prevention equipment and drilling with a hydraulically operated power swivel.
4. Drill through the coal seams and innerburden with water. Allow the well to flow while drilling and produce solid material, gas, and water to a flare pit.
5. Pull the drill bit up into the casing. Pressure up the wellbore and near-well region with air and water. Allow the pressured well to blow out to a pit.
6. Periodically drill back to the original total depth of the well while circulating solid material to surface. Continue circulation until the wellbore remains relatively free of solid material.
7. Repeat the injection, blow out, clean out procedure until the cavity is stabilized. Stabilization is deemed to occur when production of solids is minimal or non-existent and when fluid production rates are not improved by continued cavitation.
8. Install the tubing and wellhead equipment and move the completion rig off location.

The exact procedures differ due to the operator's preferences. One difference is that some operators run a pre-drilled, hydraulically set liner across the open hole interval to reduce coal production problems. Other operators feel that additional cavitation time can stabilize the coal seams, eliminating the need for the liner.[9]

COAL NATURAL FRACTURE SYSTEMS

Commercial productivity of coal reservoirs is dependent upon an interconnected natural fracture system. The natural fractures are termed cleats. The cleats are the conduits for production of gas from the coal matrix to wells. The primary cleats present in the coal are commonly known as "face" cleats. Secondary cleats are referred to as "butt" cleats. Secondary cleats terminate in the more laterally continuous primary cleats and must have formed after the primary network. Additional third and fourth order cleat networks are also common and are generally in order of decreasing lateral continuity.[10,11] The degree of lateral continuity variation is believed to account for an anisotropic permeability distribution. The permeability is a function of stress due to the small size of the openings.[12]

HYPOTHESES CONCERNING CAVITY WELL PERFORMANCE

Hypotheses concerning why Fruitland cavity wells often outperform hydraulically fractured wells fall into several categories including but not limited to the following:

Hypothesis #1

The openhole cavity technique may effectively access primary (face), secondary (butt), and other cleats.

This hypothesis is the primary reason for the improved cavity well productivity. The cavitation process increased the connectivity to the coal natural fracture system. The portion of the reservoir that is contributing to production after cavitation is different than the portion of the reservoir that was contributing prior to cavitation.

Hypothesis #2

The openhole cavity technique avoids formation damage resulting in greater productivity than a cased, fractured well.

Formation damage is minimized by using formation water free of solid material rather than mud for drilling through coals and by avoiding casing and cementing operations. Fruitland Formation coals are highly subject to formation damage. The deliverability of the coal intervals is often reduced to 50% of the undamaged open hole potential within hours of drilling through the intervals with mud. This fact has been illustrated by numerous analyses of drill stem test data collected as part of the GRI Western Cretaceous Coal Seam Project.[13,14,15] Tests attempted through perforations after running and cementing casing and prior to stimulation have performed dismally. The deliverability of the post-casing, pre-stimulation tests have been between 5% and 15% of the undamaged open hole potential.[16]

At the present time, we believe the damage to permeability is due to one or all of the following mechanisms:

a. plugging of the cleats with mud and/or cement solid material;

b. sorption of drilling, cement, and stimulation chemicals that induce swelling of the coal matrix resulting in a reduction in the cleat aperture width and permeability;[17]

c. swelling of clays induced by contact with incompatible waters that cause a reduction in cleat aperture width and permeability.[18]

Hypothesis #3

Hydraulic fractures in coal reservoirs are less effective than desired due to a number of problems.

These problems are believed due to one or a combination of the following possibilities:

a. There is evidence that suggests that the hydraulic fractures do not cross-cut face cleats that are the most permeable pathways for fluid flow.[19,20,21,22,23] As a result, the deliverability of hydraulically fractured wells may be controlled by the lower permeability butt cleats thereby reducing the deliverability. Due to the smaller aperture width and lesser conductivity of the butt cleats relative to that of the face cleats, the butt cleats may be even more susceptible to damage.

b. The effective length and conductivity of the hydraulic fracture may be much less than designed due to complex induced fracture geometries[19,24] and lithologic variation within a coal reservoir.

c. Fracture fluids used to carry proppant cause formation damage that reduces near hydraulic fracture cleat permeability.[17]

d. Hydraulic fracture gels may not break completely or may leave significant amounts of gel residue that may plug cleats. This possibility may be partly due to lack of sufficient quality control while performing the stimulations.[25]

e. Hydraulic fracture emplacement may cause increased horizontal stress and cleat aperture decrease with a corresponding permeability decrease in the reservoir adjacent to the induced fracture.[26]

f. The hydraulic fractures may propagate partially out of zone resulting in a shorter effective fracture length in the reservoir interval.[27,28]

We have observed one post-hydraulic fracture stimulation test that suggests that the near-induced fracture permeability has been reduced.[19] This observation supports hypotheses c, d, and e.

Hypothesis #4

Reservoir permeability in the area surrounding the cavity may increase due to stress relaxation and subsequent cleat aperture increase.

This hypothesis was based upon observations of the stress distributions around coal mines.[29] The original paper also described a scenario where the diffusion rate from the coal is increased by continuous spalling of coal into the cavity. Spalling would result in a reduction of the average particle size controlling diffusion thereby increasing the diffusion rate.

These are not the mechanisms that result in improved recovery and production rates at the COAL Site. Near-well absolute permeability was believed to be temporarily increased but returned to the original level after 48 days of production. Continuous spalling of the coal was not observed as coal fines were not produced during production. Material balance calculations performed during reservoir simulation supported the conclusion that the gas originated in the coal matrix.

COAL SITE RESEARCH EFFORT

To evaluate and compare the completion types, GRI, Amoco Production Company (Amoco) and Resource Enterprises, Inc. (REI) created the COAL Site. The Site is located on the Southern Ute Indian reservation in La Plata County of southwestern Colorado. The primary focus of the research was to collect and interpret data concerning the performance of an open hole cavity well in a described, controlled environment. To quantify the reservoir description, the effort included extensive coring, core analysis, logging, and well testing efforts in two observation wells.

The Site geometry is illustrated in Figure 1. The newly drilled open hole cavity well, Southern Ute Tribal I PLA 9 #2 (hereafter referred to as the I#2 well) was the primary well of interest.

GRI Observation Well #1 (GRI#1), a newly drilled pressure observation well, is located 54.28 meters (178.1 ft.) north, 41 degrees 7 minutes west, of the I#2 location. The GRI#1 location was selected to be close to the cavity well to obtain accurate estimates of permeability changes that may have occurred during cavity installation. The orientation between the two wells is such that the butt cleat permeability should have controlled the pressure response during interference testing.

GRI Observation Well #2 (GRI#2), a second newly drilled observation well, is located 325.9 m (1,069.1 feet) south, 65 degrees 50 minutes west, of the I#2 location. The GRI#2 location was selected to be sufficiently far from the cavity well to estimate the distance from the cavity well that permeability changes may have occurred during cavity installation. The orientation is such between the two wells that the face cleat permeability should control the pressure response during interference testing.

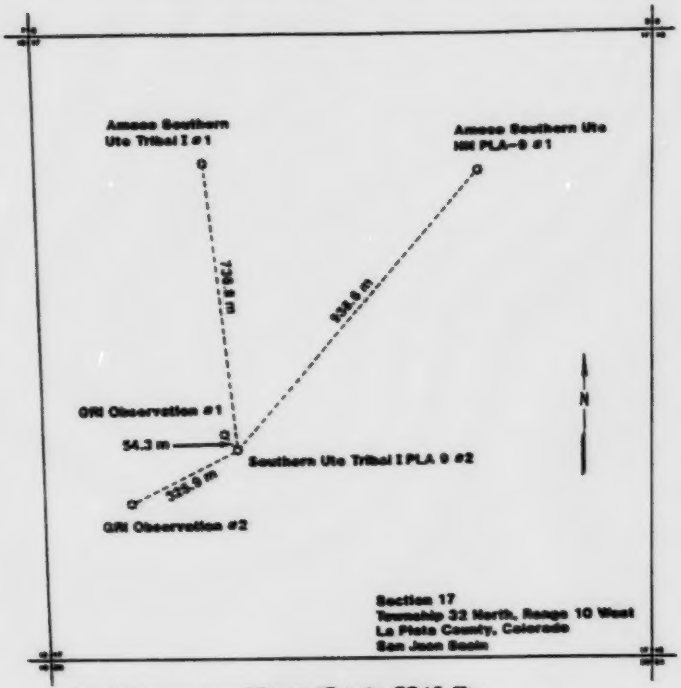
The existing hydraulically fractured Southern Ute Tribal I-1 well was converted from a production well to a pressure observation well. The existing hydraulically fractured Southern Ute Tribal NN production well was equipped with a bottomhole pressure gauge for performance monitoring.

The location for the COAL Site was chosen to be in an area where the probability of a successful cavity installation was high and where offset well control would allow comparisons between productivity of completion types. Three wells near the COAL Site had been cavitated in the past. Seven nearby wells had been hydraulically fractured. Initial gas production rates for the seven hydraulically fractured wells averaged 28,000 to 40,000 m^3/D (200 to 1,400 MSCF/D) whereas the initial gas rates for three cavity wells averaged 40,000 to 99,000 m^3/D (1,400 to 3,500 MSCF/D). The productivity differences are believed due to the completion practices as the maximum distance between the wells is 2.5 miles and the Fruitland Formation basal coal zone stratigraphic and structural variation in this area is minor.

Figure 2 illustrates the density log measured in the GRI #1 well. The character of the log in the GRI#2 is quite similar with some lithologic variations. There are two coal intervals of interest in the area that we informally refer to as the "upper" and "basal" Fruitland coal intervals. An extensive data collection operation was performed to characterize the reservoir properties.[16]

The coal seams in the upper interval were cored, drill stem tested, and logged. Extensive core analyses were performed. The

Section 17 COAL Site Well Locations


Amoco Southern
Ute Tribal I #1
Amoco Southern Ute
NM PLA-9 #1
738.8 m
838.6 m
N
GRI Observation #1
54.3 m
Southern Ute Tribal I PLA 9 #2
325.9 m
GRI Observation #2
Section 17
Township 32 North, Range 10 West
La Plata County, Colorado
San Juan Basin

Detailed map view of Secton 17 at the COAL Site

Figure 1

GRI OBSERVATION WELL #1

NEAR OBSERVATION WELL

OPERATION SCHEMATIC

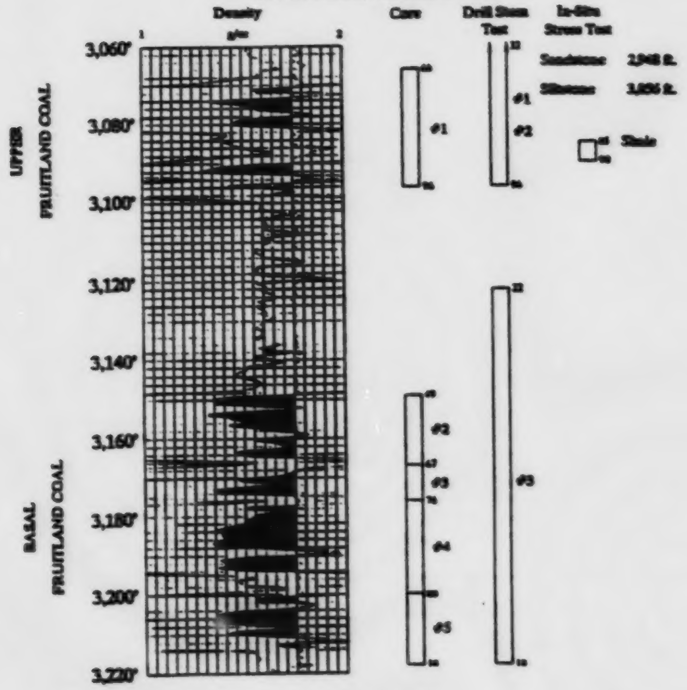


Figure 2

upper interval has insufficient permeability to produce fluids or to affect interference test pressure response. As a result, we did not evaluate the upper interval in the GRI#2 well nor monitor pressure changes in this interval.

The basal coal seams were cored, drill stem tested, and logged in both the observation wells. This interval is very permeable. The reservoir properties that have obtained to date from core, log, and well test analyses are listed in the following table for each of the three wells.

Table 2. Summary of COAL Site Basal Coal Property Estimates

		Well		
Property	Units	I#2	GRI#1	GRI#2
Geometry				
Depth to the top of the coal	m	949.31	959.66	963.32
Depth to the bottom of the basal coal	m	979.63	979.23	1,003.9
Basal coal thickness	m	15.6	14.17	13.11
Coal Matrix Properties				
In-situ gas content	cc/g		17.59	17.22
Average ash content	%		29.9	30.2
Langmuir volume (dry, ash free)	cc/g		34.90	-
Langmuir pressure	kPa		4,178.2	-
Sorption time	hours		4.0	4.2
Average coal density	g/cc		1.499	1.502
Cleat System Properties				
Temperature	^oC	48.9		
Initial pressure	kPa	10,685.2	10,685.2	10,685.9
Pressure datum (1,038.1 m ASL)	m	975.06	975.36	986.94
Test derived absolute permeability	μm^2	0.0243	0.0222	0.0190
Average cleat horizontal permeability	μm^2	0.0148		
Face cleat absolute permeability	μm^2	0.0247		
Butt cleat absolute permeability	μm^2	0.0089		
Face to butt cleat permeability ratio	-	2.8		
Porosity	%	2		
Initial water saturation	%	100		
Pore volume compressibility	1/kPa	$4.79(10^{-5})$		
Fluid Properties				
Methane concentration	%	87.927		
Carbon dioxide concentration	%	11.527		
Gas viscosity at reservoir conditions	Pa-s	$1.46(10^{-5})$		
Gas formation volume factor	-	$9.169(10^{-3})$		
H_2O viscosity at reservoir conditions	Pa-s	$5.5(10^{-4})$		
H_2O formation volume factor	-	1.01		

Relative permeability to gas and water was based upon published laboratory data[30]. Later measurements performed on GRI#1 samples confirmed the accuracy of the published information.[31] The pore volume compressibility estimate was obtained from laboratory measurements.[32] The properties listed above are those that are required to predict well deliverability and interwell pressure behavior with a coalbed natural gas reservoir simulator.

I#2 CAVITATION OPERATIONS

During the cavitation activities performed on the I#2 well, there were five basic periods as listed in Table 3.

Table 3. Cavitation Periods

Period	Description
1	Injection Cavitation Period
2	Natural Cavitation Period
3	Flow Period
4	Production Test Period
5	Clean Out Period

During an injection cavitation period, the drill bit was pulled into the casing above the open hole interval. Pipe rams were closed around the drill pipe. Two hydraulically operated valves in two 0.15 m (6 inch) diameter blooie lines were closed preceding injection to provide a pressure seal at the surface. Generally, 4 m^3 (25 barrels) of water were injected first followed by air injection at rates between 63.7 and 85 m^3/min (2,250 and 3,000 standard cubic feet per minute-cfm) into the reservoir. Surface pressures at the end of injection ranged from 5,516 to 10,340 kPa (800 psig to 1,500 psig) depending partly upon the length of the injection periods which ranged from 11 minutes to 2.8 hours. In most cases, after the initial 4 m^3 of water, air was the only injection fluid used. During several injection cavitations, both air and water were used following the initial 4 m^3 of water. At the end of the injection period, a flow period was started by opening the hydraulically operated valves on the blooie lines and allowing the well to violently blow out to a flare pit. There were a total of 20 injection cavitations used to stimulate this well.

During a natural cavitation period, the drill bit was pulled into the casing and the pipe rams and hydraulically operated valves were closed. The surface pressure was allowed to increase to 3,450 kPa (500 psig) which generally required 15 to 30 minutes. Once 3,450 kPa was reached, the hydraulically operated valves were opened allowing the well to violently blow out to a flare pit. The natural cavitations were the most spectacular as the size of the flare was huge. A total of 29 natural cavitations were used to stimulate the I#2 well.

Flow periods are those in which the well was allowed to flow to a pit through the blooie lines without the injection of air to assist production. Flow rates during flow periods were not estimated.

During production tests, flow was diverted through a choke manifold to produce through test lines to the pit rather than through the blooie lines. Gas flow rates were estimated from the pressure drop across the choke.

Large volumes of coal were produced into the well during the flow periods. During the clean out periods, the drill pipe was drilled to the total depth of the well while injecting between 63.7 and 85 m^3/min (2,250 and 3,000 cfm) of air down the drill pipe. A stripping head was closed around the drill pipe to provide a pressure seal of up to 1,380 kPa (200 psi). The hydraulically operated valves on the blooie lines were open allowing the well to flow to a pit. Water was also circulated during the clean out period to assist in lifting the solid material to surface and out of the well. To improve lifting capacity, injection of between 0.8 and 1.6 m^3 (5 and 10 bbls) of a soap solution was included at periodic intervals to foam the water.

Figure 3 illustrates the volumes of water and gas that were injected into the reservoir during the injection cavitation periods. This figure also represents the natural cavitations as periods with negative injection. The negative injection rate is only a representation and is not an estimate of the production rates that actually occurred. The total volume of gas and water injected during the stimulation was 1,161 reservoir m^3 (7,304 bbls) and 153 reservoir m^3 (960 bbls), respectively.

Figure 3 also lists the estimates of gas production rates that were obtained at various times during cavitation. An early gas production rate of 2,800 (100 MSCF/D) was obtained after the first cavitation. After the first day of cavitation that included six injection cavitation and flow periods, gas production rates increased quickly to between 15,900 to 23,800 m^3/D (560 to 840 MSCF/D). An additional three injection cavitations and four natural cavitations increased the deliverability to 30,600 m^3/D (1,080 MSCF/D) at the end of Day Four. Injection cavitations during Day Five followed by two natural cavitations increased the deliverability to the maximum level of between 51,000 and 62,000 m^3/D (1,800 and 2,200 MSCF/D).

During Day Six, large amounts of coal were removed from the well. Cavitations were not performed between the clean out periods. Day Seven consisted of 20 natural cavitations.

After performing 6 very large injection cavitations during Day Eight, gas production rates of 30,600 to 51,000 m^3/D (1,080 to 1,800 MSCF/D) had not been increased over the levels observed during Day Five. Day Five cavitations had the most effect upon reservoir properties. Day Seven and Eight cavitations resulted in no improvement in gas deliverability. This conclusion is supported by the pressure data that was observed at GRI#1.[16]

CAVITY VOLUME DETERMINATION

Three techniques were used to attempt to obtain estimates of the cavity dimensions. Sonar logging[33] was performed to obtain a three dimensional representation of the cavity radii as a function of angle and depth. The volume and weight of solid material that was produced to surface during the cavitation operations was determined. The solid material volume confirmed the value estimated from the sonar log. A third technique based upon hydraulic impedance[34] was attempted but failed to yield accurate estimates.

Figure 4 illustrates the sonar log that was obtained to a maximum depth of 973.8 m (3,195 ft.). The bottom 2.6 meters (8.5 ft.) of coal between 976.6 to 979.6 m (3,204 and 3,214 ft.) were not logged. Track two of the log illustrates the average cavity radius and diameter. Track three illustrates the gamma ray data from the I#2 well. Track four contains the gamma ray and density data from the GRI#1 well.

The majority of the coal seams in the basal interval appeared to cavitate. Interbedded shales and tonsteins did not appear to cavitate in either the basal or upper Fruitland intervals. This observation was confirmed by the fact that the cuttings recovered from the well appeared to be largely coal and not other matter. The upper Fruitland seams (not included in Figure 4) did not appear to cavitate.

The sonar log is operated by suspending the tool at a depth of interest and obtaining 24 radius readings at equally spaced angular rotations (15°) at a horizontal inclination. The tool is then moved to the next depth of interest and the process is repeated. Only radii greater than approximately 0.91 m (3.0 ft.) can be measured due to the calibration of the sonar log. Radii less than 0.91 m are reported as 0.88 (2.9 ft.) to 0.91 m. As a result, it is not possible to determine if the degree of cavitation is such that the radius in any direction is less than 0.9 m. Radii reported as 0.88 to 0.91 m in intervals not believed to have cavitated were adjusted to 0.07925 m (0.2604 ft.) which was equal to the radius of drill bit.

The maximum diameter that was observed was 3.9 meters (12.8 feet). The volume of the cavity between 960.1 m (3,150 ft.) and the deepest logged point of 973.8 m (3,195 ft.) was 60.7 m^3. The 2.6 meters of coal that were not logged were believed to have a volume of 15.3 m^3. Total cavity volume was 76.0 m^3.

To obtain confirmation of the volume of the cavity, the volume and weight of produced coal was determined by collecting approximately 50% of the material in a dual tank arrangement designed by Amoco.[35] The remainder of the coal was trapped in the flare pit, the trench connecting the flare pit with the drilling fluid reserve pit, and the reserve pit.

A total of 87.2 m^3 of coal was produced. Based upon an unconsolidation factor of 0.8162 determined by the material density,[16] the down-hole volume estimate was 71.1 m^3. This value is within 6.4% of the sonar log value and supports the sonar log cavity geometry determination.

COAL SITE WELL TEST ANALYSES

Application of well testing technology was a major effort during this project. Single well tests of each of the three major wells were performed to evaluate the cleat system properties prior to cavitation. A pre-cavitation interference test was performed by producing the I#2 well and measuring the pressure response at the GRI#1 and GRI#2 locations. The interference test was repeated after cavitation to evaluate changes that may have occurred due to the completion process. This section discusses the results of the evaluations that were performed.

Southern Ute Tribal I Pla 9 #2
Cavitation Fluid Injection Volumes

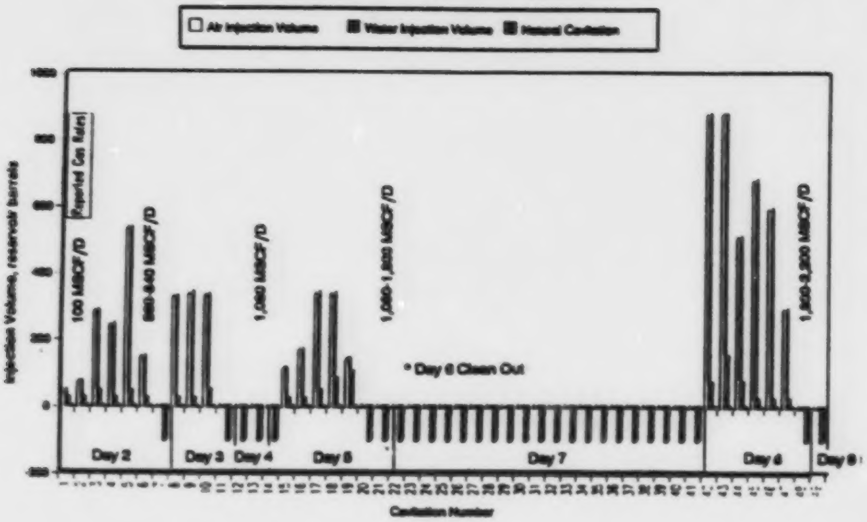
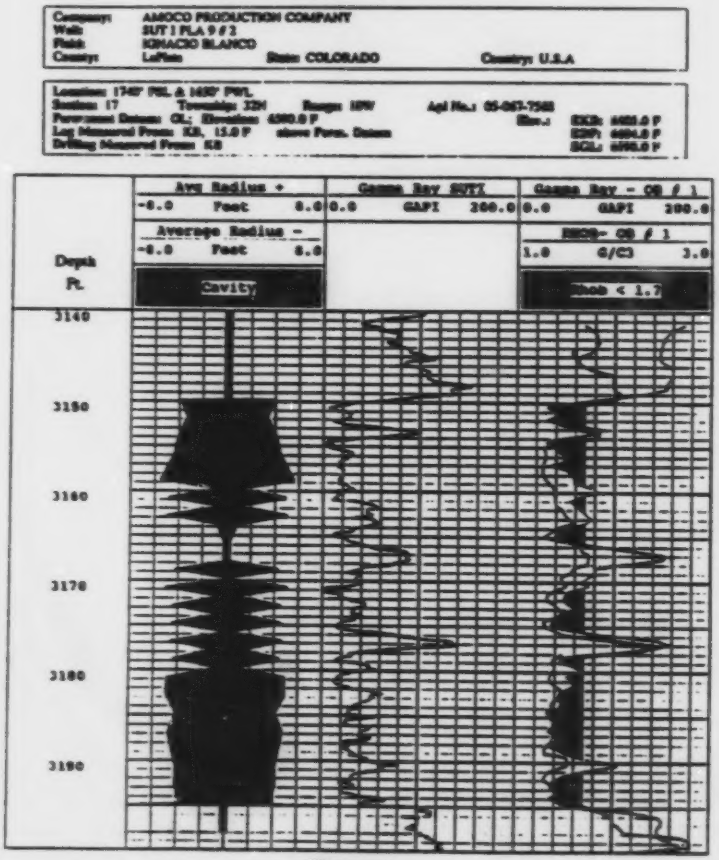


Figure 3

Open Hole Cavity Dimensions



Company: AMOCO PRODUCTION COMPANY
Well: SUT I PLA 9 # 2
Field: IGNACIO BLANCO
County: LaPlata State: COLORADO Country: U.S.A

Location: 1740' FSL & 1650' FWL
Section: 17 Township: 32N Range: 10W Api No.: 05-067-7568
Permanent Datum: GL; Elevation: 6590.0 F Elev.: EKB: 6605.0 F
Log Measured From: KB, 15.0 F above Perm. Datum EDF: 6604.0 F
Drilling Measured From: KB EGL: 6590.0 F

Figure 4

The pre-cavitation interference test consisted of a 48 day flow period followed by a 55 day shut-in period. It was necessary to pump the I#2 well to maintain average gas and water production rates of 3,030 m^3/D and 19.1 m^3/D (107 MSCF/D and 120 STB/D), respectively, at a bottomhole pressure of 4,830 kPa (700 psia).

Prior to cavitation, the I#2 well had the lowest fluid deliverability of the three major wells even though the observation wells were drilled with mud. The I#2 was drilled underbalanced with formation water. Both observation wells appeared to be more damaged than the I#2 well but in better communication with the natural fracture system. A hypothesis for the poorer performance of the I#2 well will be discussed shortly.

The I#2 flowed gas and water at rates of 39,600 m^3/D and 11.3 m3/D (1.4 MMSCF/D and 400 STB/D), respectively, after cavitation. The cavitation process increased the gas production rate by a factor of 13.1 and the water production rate by a factor of 3.3 at approximately the same bottomhole pressure. The post-cavitation interference test consisted of a 5 day initial flow period, a 3.8 day initial shut-in period, a 28 day final flow period, and a 46 day final shut-in period.

Analysis of the interference data at the observation wells was performed by history matching the observed performance between the I#2 and the observation wells with the line source solution.[36] Although this model assumes that the reservoir properties are uniform and does not include dual storativity reservoir behavior, excellent matches were obtained with the observed data. More sophisticated models including wellbore storage and skin effects,[37] dual storativity reservoir behavior,[38] and vertical, infinite conductivity fractures[39] did not alter the analysis results. A summary of the key analysis results that were obtained with the line source solution are listed in the Table 3.

Table 3. Comparison of Interference Test Results

		GRI#1		GRI#2	
Parameter	**Units**	**Pre-Cav.**	**Post-Cav.**	**Pre-Cav.**	**Post-Cav.**
Transmissivity	$\frac{\mu m^2\text{-}m}{Pa\text{-}s}$	297	975.9	886.4	578.8
Diffusivity	$\frac{\mu m^2\text{-}kPa}{Pa\text{-}s}$	$3.53(10^6)$	$2.41(10^6)$	$7.20(10^6)$	$4.09(10^7)$
Permeability	μm^2	0.0089	0.0128	0.0247	0.0232
Thickness	m	11.58	14.17	11.43	4.34
Porosity	%	2.0	2.0	2.85	2.85
Total Compressibility	$\frac{1}{kPa}$	$3.6(10^{-4})$	$1.4(10^{-3})$	$3.8(10^{-4})$	$1.1(10^{-4})$

Cavitation did not greatly affect the estimated interwell permeability between the I#2 and the GRI#1 well located in the butt-cleat orientation. The estimates of the absolute permeability varied from 0.0089 μm^2 (9 md) prior to cavitation to 0.0128 μm^2 (13 md) after cavitation. The average estimate is 0.0128 μm^2 (11 md). This permeability estimate was assumed to be equal to the butt cleat permeability as the two wells are oriented in the butt cleat direction.

The difference between the pre- and post-cavitation estimates are not considered significant as inaccuracies are expected due to large fluid saturation and pressure changes between the two wells. We are continuing our evaluation of the data by history matching the pressure response with a coalbed natural gas reservoir simulator[40] that can be used to predict the saturation distribution. Hopefully, this added capability will improve the accuracy of the analysis.

The match between the observed and computed pressure response at th GRI#2 well is more accurate than for the GRI#1 well due to smaller pressure and saturation changes between the I#2 and GRI#2 wells. There was little difference between the permeability estimates obtained from the pre- and post-cavitation tests.

There is a significant difference in the thickness of the coal that was required to match the GRI#2 data. The thickness was reduced by a factor of 2.6 from the pre-cavitation estimate to obtain an accurate match of the post-cavitation data. This adjustment may be caused by domination of the pressure response by an upper coal seam that has a thickness approximately equal to that required to match the data. We are continuing our analysis with reservoir simulation and a multi-layered well test analysis model.[41]

Evaluation of the I#2 well was based upon three shut-in tests; one performed before cavitation and two performed after cavitation. Table 5 compares the analysis results.

Table 5. Comparison of I#2 Test Analyses

Parameter	Units	Pre-Cav.	Post-Cav. Initial Shut-in	Post-Cav. Final Shut-in
Transmissivity	$\frac{\mu m^2\text{-}m}{Pa\text{-}s}$	356.9	3,011.2	1,921.9
Permeability	μm^2	0.0101	0.0569	0.0243
Thickness	m	11.58	14.17	14.17
Skin Factor	-	2.8	-2.6	-2.6
Flow Efficiency	%	71	160	160

The thickness values before and after cavitation were different as solid material covered the lowest-most 2.6 m (8.5 ft.) of coal during the pre-cavitation test.

The pre-cavitation absolute permeability estimate is approximately equal to the estimate of the permeability in the butt cleat direction. This result was surprising. The estimates of the absolute permeability obtained from drill stem tests of the GRI #1 and GRI#2 wells listed in Table 2 were similar to the face cleat permeability estimates. Why would the production behavior of a well located within 326 m (1,069 ft.) of both of these wells be controlled by a different absolute permeability?

One possibility that may explain the domination of the butt cleats prior to cavitation has been observed at the Cedar Hill Field located approximately three miles to the south of the COAL Site. The open fracture orientation in the Cedar Hill Field is in the orientation of the butt cleats based upon evaluation of three component vertical seismic profile data from the Hamilton #3 well.[42]

The combination of these two analyses may suggest the following rather radical hypothesis. The intense stress distribution around the 0.159 m (6.25 in.) diameter borehole may preferentially reduce the face cleat permeability due to the existing stress orientation that is parallel to the butt cleat direction. This direction is suggested by the seismic analysis. Upon cavitating, the radius of the borehole was increased by a factor of 16.5 that would significantly reduce the stress near the cavity and may allow greater connectivity to the face cleats.

Why are the mud drilled holes already in communication with both the face and butt cleats? There is no question that the near-well permeability of the mud drilled holes is significantly damaged. One of the possible damage mechanisms is plugging of the cleats by mud solids. As these wells were drilled overbalanced which would increase the near well cleat apertures, the mud solids may partially prop the near-well fractures allowing both the face and butt cleats to remain in communication with the well. Even so, the mud drilled wells are still poorer producers than the I#2 well after cavitation.

Analysis of the I#2 final shut-in data after cavitation indicates that the absolute permeability controlling production is approximately equal to the face cleat permeability as was the case for the mud drilled holes.

The cavitation process reduced the skin factor from approximately 2.8 to -2.6. The post cavitation flow efficiency is approximately 160%. The flow efficiency indicates that the cavity accounts for an increase in productivity of 60% and not the thirteen-fold increase observed in the gas production rates and the three-fold increase observed in the water production rates. The estimate of the skin factor due to the cavity is equivalent to that expected from the increased wellbore radius.[43] Based upon Equation 1, the skin factor due to a cavity 1.31 m (4.3 ft.) in radius is -2.8 since the original wellbore radius was 0.07925 m (0.26 ft.).

$$s_c = -\ln \frac{r_c}{r_w} \qquad (1)$$

where:

s_c skin factor due to the cavity, dimensionless
r_c average radius of the cavity, meters
r_w original wellbore radius, meters

The contention that the cavity has little effect upon productivity is supported by additional examples, one of which will be discussed in the following section. A cavity of diameter between 3 and 9 feet[20,34] was created in the 2 Deep Seam well located at the GRI Red Mountain research site in the Piceance Basin of western Colorado. The depth of the coal seams at this location is 1,676 m (5,500 ft.). The absolute permeability is quite low due to the net overburden stress and a low cleat frequency. The presence of the cavity did not substantially alter gas productivity as the gas rates were less than 3 m^3/D (1 MSCF/D).

There is evidence that the near-cavity permeability is temporarily increased. During the Day Eight cavitation operations, rapid pressure changes of 69 to 138 kPa (10 to 20 psi) were observed at GRI#1 within 1 to 5 minutes after the start of air injection. The apparent interwell permeability to create a pressure change of 138 kPa (20 psi) was 2 μm^2 (2 darcies).

Analysis of the first shut-in period following cavitation resulted in estimates of permeability that exceeded all other estimates by a factor of 2.3. The pressure behavior was characteristic of a single permeability reservoir with no evidence of an enhanced near-cavity permeability region. The apparent high estimate of permeability may be due to a temporary natural fracture permeability increase caused by the injection of air and water.

There is no evidence of improved near-cavity permeability after continued production. Figure 5 is a multi-phase potential diagnostic graph of the final post-cavitation shut-in period data. The multi-phase potential analysis[16,44] has been used to reduce the effects of fluid property dependence upon pressure and relative permeability dependence upon fluid saturations. The derivative of the potential change with respect to a multi-rate superposition function[16] eventually stabilizes and reaches a constant value. The stabilization is indicative of a single permeability natural fracture system that controls fluid movement. The estimate of the absolute permeability from this analysis is approximately equal to the face cleat permeability estimate obtained from the pre- and post-cavitation interference tests.

VERTICAL COAL SITE RESEARCH EFFORTS

A very recent evaluation effort has been performed of a cavity well drilled by Arco Oil and Gas Company (ARCO). The purpose of the evaluation was to determine effects of a cavity completion upon the vertically distributed production performance of a single cavity well and a single observation well. The analysis of the data is in the very preliminary stages but the observations at this location support the COAL Site conclusions. This section briefly describes the Vertical COAL Site research effort.

The Vertical COAL Site is located in Section 10 of Township 32 North, Range 10 West, La Plata County, southwestern Colorado. This location is approximately 5 km (3 miles) from the cavity well at the COAL Site. Two wells are involved in the project: the Southern Ute 10-1, 32-10 observation well (hereafter referred to as the 10-1 well) and the Southern Ute 10-3, 32-10 cavity well (hereafter referred to as the 10-3 well). The surface locations of the wells are separated by 49.92 m (163.78 ft.).

The 10-1 well was originally drilled in 1980 as a gas producing well in a deeper horizon and was recompleted for use as an observation well. Figure 6 illustrates a gamma ray-density log and the observation wellbore configuration. Three coal intervals of interest to the project are penetrated by both wells. The coals in all three intervals are significantly naturally fractured with estimates of absolute permeability exceeding 0.019 μm^2 (20 md).

Pre-cavitation testing was performed in the 10-1 well to obtain estimates of cleat system permeability prior to drilling the 10-3 well through the coal seams. After perforating, the lowest-most seams failed to produce and an injection-fall off test was performed. The middle seams that were believed to be the most productive, were perforated and hydraulically fractured with a small water and proppant stimulation. A post-frac production and shut-in test was performed in the middle interval. Test results of the upper coal interval were the most surprising.

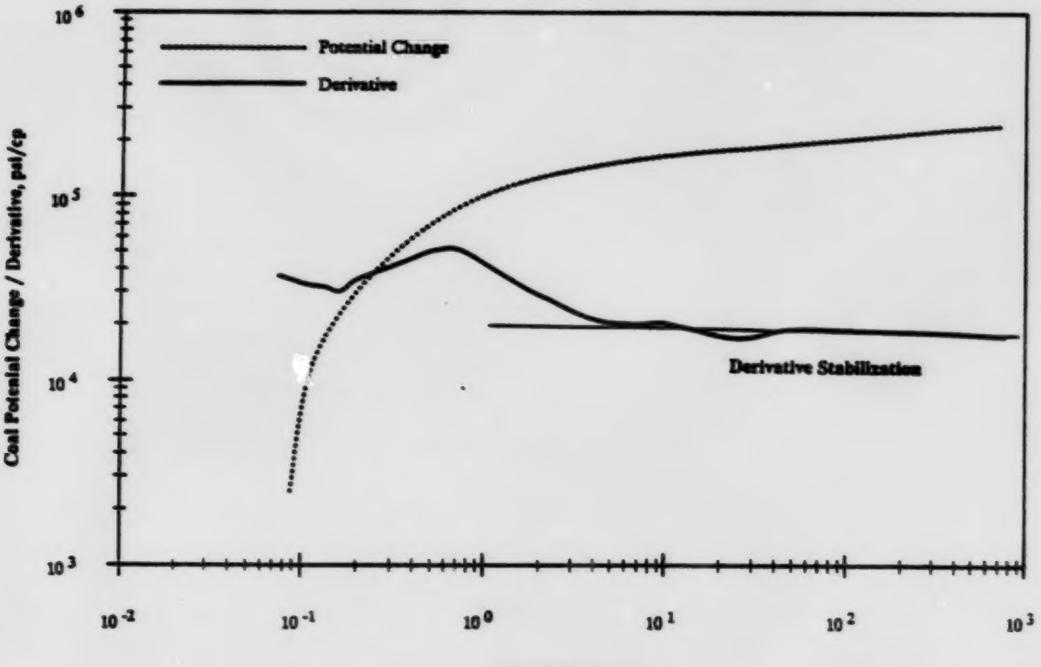
After isolation and perforation of the upper seams, the well produced between 17,600 and 27,000 m^3/D (622 and 954 MSCF/D) of gas. Water rates were between 1 and 1.7 m^3/D (40 and 60 STB/D). This is the only pre-stimulation test out of twenty in which we have observed significant gas production after running and cementing casing. We believe that the upper seams were contacted by a minimal cement volume as the cement bond across the upper coal seams was very poor. Even so, mud was in contact with the coal for eleven years and failed to damage the coal enough to prevent production.

After testing was completed, the 10-1 well was configured to monitor pressure changes in each of the three intervals as illustrated in Figure 6. Each interval was completely isolated from the others.

When drilling through the coal seams in the 10-3 well, an open hole production test was performed in the upper seams. After the test was completed, drilling continued to just below the lowest-most seams and a four day production and shut-in test was performed. Following the testing, the well was cavitated following procedures similar to those at the COAL Site with the exception that very little water was injected into the reservoir.

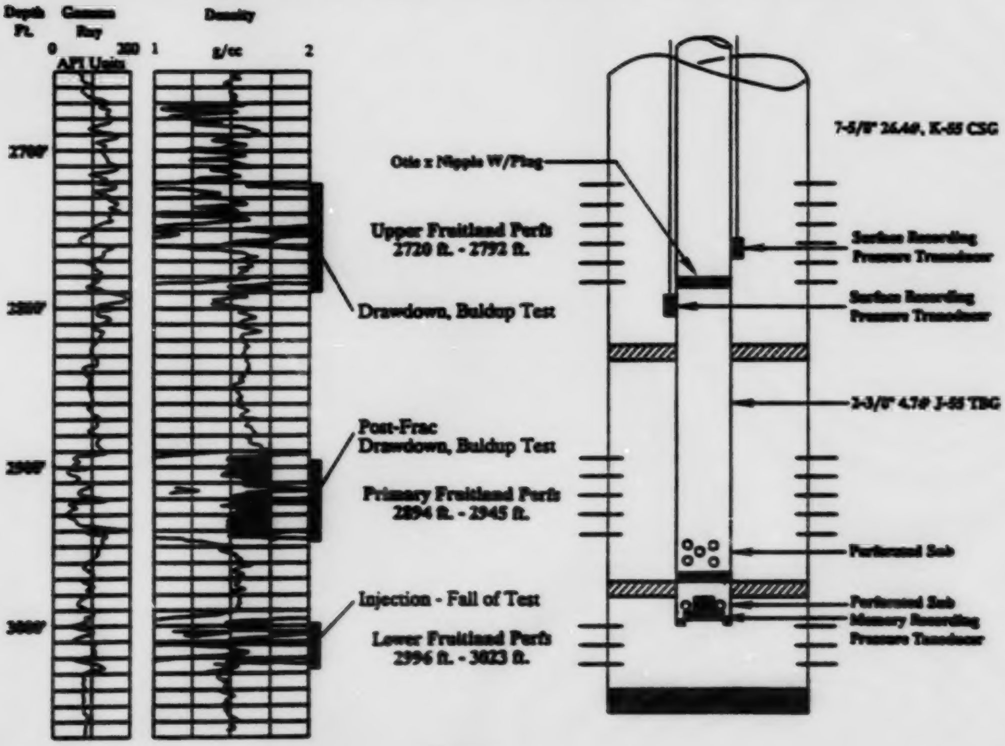
Cavitation of the 10-3 well did not increase the gas production rates from the pre-cavitation levels even though a cavity with the same volume per unit coal thickness as the I#2 cavity was created. The apparent failure of the cavitation procedures is believed due to the fact that the fracture system of the upper seams was in effective communication with the well prior to cavitation. As connectivity was already established, cavitation did not improve the productivity. This lack of gas productivity increase even though a cavity was created is very unusual. Usually, when production cannot be increased, a cavity can not be created.[45]

Water production rates were increased by the cavitation process. We concluded that 80% of the water originated in the lower two



Southern Ute Tribal I Pla 9 #2
Post-Cavitation Second Shut-in Test Diagnostic Graph

Figure 5



Summary of Operations at the Southern Ute 10-1, 32-10 Observation Well

Depth Ft.
Gamma Ray
0
200
API Units
Density
1
g/cc
2
2700'
2800'
2900'
3000'
Upper Fruitland Perfs 2720 ft. - 2792 ft.
Drawdown, Buldup Test
Post-Frac Drawdown, Buldup Test
Primary Fruitland Perfs 2894 ft. - 2945 ft.
Injection - Fall of Test
Lower Fruitland Perfs 2996 ft. - 3023 ft.
7-5/8" 26.4#, K-55 CSG
Otis x Nipple W/Plug
Surface Recording Pressure Transducer
Surface Recording Pressure Transducer
2-3/8" 4.7# J-55 TBG
Perforated Sub
Perforated Sub
Memory Recording Pressure Transducer

Figure 6

coal intervals. Table 7 compares the gas and water production rates that were observed.

Table 7. Summary of Vertical Coal Site Production Rates

Well	Test	Gas Rate	Water Rate
		m^3/D	m^3/D
10-1	Lower coal injection-falloff	0	-8.1
	Middle coal post-frac	280	8.9
	Upper coal production	27,000	1.7
10-3	Upper coal pre-cavitation	31,300	2.9
	All coal pre-cavitation	30,400	8.6
	All coal post-cavitation	32,600	14.7

Although short-term gas productivity was not improved, it is possible that long term gas productivity may be significantly altered by the cavitation process. The connectivity to the lower two seams was improved as evidenced by the increased water production rates. As these seams are dewatered, the rates of gas production may increase significantly.

A sonar log could not be successfully run as rugose borehole conditions prevented the tool from reaching the bottom of the well. A diameter of 4.9 m (16 ft.) was observed in the upper seams indicating that the upper seams were cavitated. The volume of the cavity was 159 m^3 (5,600 ft^3) based upon the volume of solid material remaining on location after cavitation. This volume is 2.1 times the volume of the I#2 cavity. The 10-3 well net coal thickness is 27.43 m (90 ft.) compared to 14.17 m (46.5 ft.) at the I#2 location indicating that the cavity volume per unit thickness is approximately the same at both locations.

We would expect the presence of the cavity to increase the gas productivity by 60%. The reason that it was not increased is that the bottomhole flowing pressure after cavitation was greater than the flowing pressure prior to cavitation due to additional water production.

CONCLUSIONS

Based upon the evaluation of data at both research sites, we have arrived at the following conclusions.

The cavity completion effectively links the wellbore with the natural fracture system of the coal reservoir. The increased fluid productivity is due to more effective linking than existed prior to cavitation and not due to the cavity.

The cavity accounts for a 60% increase in the fluid productivity.

Formation damage is minimized by the lack of contact between the coal reservoir rock and drilling fluids.

At the COAL Site, the deliverability of gas and water to the well prior to cavitation was controlled by butt cleat conductivity.

At the COAL Site, the deliverability of gas and water after cavitation is controlled by a conductivity equal to the face cleat conductivity.

At the COAL Site, the near-cavity permeability appears to be temporarily increased during the cavitation operations. The near-cavity permeability increase is non-existent after extended production.

Cavitation of the cavity well at the Vertical COAL Site did not improve the gas productivity since the uppermost coal seams were in effective communication with the well prior to cavitation.

ACKNOWLEDGEMENTS

The support for this project was provided by the Gas Research Institute. The Resource Enterprises, Inc. research staff consists of the author and R.N. Britton, J.C. Close, R. Copenhafer, R. Dhir, T.L. Logan, R.B. Marshall, and T.J. Pratt all of whom made very significant contributions to the project. The COAL Site effort could not have been performed without the contributions of J. McAnear, K. Sauvageau, F. Thomas, G. Kempton, D. Keeny, and B. Fultz of Amoco Production Company. The Vertical COAL Site efforts could not have been performed without the contributions of C. Webb, M. Ward, G. Holcom, G. Creamer, and S. Robinson of Arco Oil & Gas Company.

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OPTIMIZATION OF GEOTECHNICAL AND ECONOMIC FACTORS INFLUENCING COALBED METHANE EXPLORATION PROJECTS

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Coalbed methane (CBM) has accounted for over 80% of the increase in US natural gas reserves since 1989 and now constitutes approximately 5% of the country's proven natural gas reserves. In an effort to replicate successful CBM projects, operators have placed an emphasis on detailed geologic evaluations, determination of specific inherent coal characteristics, the evolution of new completion techniques, the optimization of marketing and other economic parameters, and recognition of the uniqueness of each project.

Although originally intended to promote development of CBM in all areas, US tax incentives have served to concentrate development in established producing areas. Tax-credit-driven project mentality, drilling deadlines for tax credit qualification, and depressed natural gas prices have resulted in most project financing, and the associated technological development, being focussed in traditional producing regions such as the San Juan and Warrior basins. Typically characterized by well-documented stratigraphic relationships, relatively quiescent structural settings, and a mature infrastructure of petroleum industry services, producing areas create attractive targets for qualifying large natural gas reserves for tax credit assistance. While advances in drilling, completion, production and geotechnical engineering have occurred and are generally applicable to coal behavior and CBM development, comprehensive project models from these areas are not always appropriate for frontier areas.

One of the first multi-well attempts to define the geological, engineering and economic parameters necessary to produce CBM from tectonically-complex, operationally remote, and sparsely tested geological settings commenced in western Washington state during 1987. Five (5), 3900' test wells were drilled into multiple, steeply-dipping, coalbeds of the Puget Group (Late Eocene). Preliminary testing results indicate an in-place resource base of greater than 18 billion cubic feet of pipeline-quality natural gas (99% CH4, 952 Btu) per 640 acres. In close proximity to the large natural gas markets of western Washington state, currently with no indigenous natural gas supply, such findings have significant value.

The on-going CBM exploration and drilling activity in Washington state may result in the establishment of economic natural gas production in a relatively complex geologic and economic setting. In as much as many coal regions in western North America exhibit similar complex geologic, operational and economic conditions, a better model for the potential exploration and development of CBM reserves in the Cretaceous coal basins of Vancouver Island may be constructed.

NOTES

COAL BED METHANE RESEARCH AT THE ALBERTA GEOLOGICAL SURVEY

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The Alberta portion of the Western Canada Sedimentary Basin contains over 7.7 x 10^{12} tons (7 x 10^{12} tonnes) of coal ranging in rank from lignite to semianthracite. These coals are distributed throughout the mountains, foothills and plains regions and range from Jurassic to Tertiary in age. Promising geologic settings for coal bed methane recovery are found in all three regions.

The first testing of Alberta coals for methane began in 1974. The Alberta petroleum industry has recently shown renewed interest and companies have begun testing samples and acquiring land positions. The deep coal resources of the province have received little attention despite being penetrated by thousands of petroleum exploration and production wells. A recent industry supported resource evaluation study by the Alberta Geological Survey defined the stratigraphic and structural framework of the coals throughout the province through production of an extensive suite of cross-sections and maps. Regional trends in subsurface coal ranks were defined for the whole province for the first time by collecting hundreds of vitrinite reflectance measurements. While the detailed results of the study remain confidential, it has provided the basis for on-going studies by several participants.

A modest level of industry activity is taking place in the province, several companies have combined testing of coals with drilling programs aimed at deeper horizons while a few test holes have been drilled specifically for coal bed methane. Current activity at the Alberta Geological Survey is focussed on the establishment of a Coal Bed Methane Research cooperative to permit participants to leverage their research resources while focussing on their areas of highest priority. Estimates of the coal resource in the province are currently being revised and improved. An extensive coal database is continually being updated and enlarged to provide information to coal related projects.

NOTES

COALBED METHANE RESOURCES IN BRITISH COLUMBIA

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Coalbed Methane in British Columbia is a resource administered under the Petroleum and Natural Gas Act by the Ministry of Energy, Mines and Petroleum Resources. Currently, Coalbed Methane is administered in the same manner as convential natural gas. Ownership, economic, environmental and land use issues are being reviewed by the Government.

Recent Ministry studies estimate potential resources of coalbed methane of 28 billion cubic meters on Vancouver Island, 3.6 trillion cubic meters in the Northeast Coalfield, and 3.5 billion cubic meters in the Tuya and Telwa deposits in northwest B.C. (Pers. Comm. C. Kenyon, EMPR). Potential resources of 493-600 billion cubic meters are identified in the Crowsnest, Elk Valley and Flathead coalfields of southeast B.C. (EMPR Petroleum Geology Special Paper 1991-1. By comparison, the total discovered conventional natural gas reserves for the whole province are 454 billion cubic meters with remaining reserves of 230 billion cubic meters.

NOTES

COALBED METHANE POTENTIAL IN NORTHEAST BRITISH COLUMBIA

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Significant coal resources occur in the lower Cretaceous Gething Formation (Aptian) and Gates Formation (Albian) in northeast British Columbia. The outcrop zone has been extensively explored since the publication of D.F. Stott's GSC Bulletin 152 in 1968. The coal exploration in the area has resulted in the opening of two large open pit coal mines in 1982.

The stratigraphy of the area is characterized by a series of continental margin transgressive/regressive sequences consisting of interstratified non-marine and marine sediments deposited in deltaic coastal plain or paralic environments. The predominantly continental and coal-bearing Gething and Gates formations are separated by the marine Moosebar Formation with marine influence generally increasing to the north. Structurally the formations are highly deformed along the outcrop zone (inner foothills). Major structures included chevron and box folds along with thrusts faults with displacements exceeding 700 metres.

Resources were measured based on coal thickness, coal rank, hydrostatic pressure and adsorption data. The potential of the area was further divided into deep and shallow resources using the 1800 metre depth to the top of the Gething formation from the isoburden map. Shallow (<1800 m) resources are estimated at 57 Tcf and deep (>1800) m) resources at 51 Tcf for a total of 108 Tcf. This translates into areas that contain up to 60 Bcf/section along the zone of potential commercial extraction which parallels the outcrop zone.

NOTES

STABLE ISOTOPE GEOCHEMISTRY OF COALS, HUMIC KEROGENS, AND RELATED NATURAL GASES

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ABSTRACT

Isotope systematics are well defined for conventional sapropelic, Type II kerogens and their associated bacterial and thermogenic natural gas products. These geochemical tools are used to estimate source type, maturity and depositional environment, and as a correlation technique. In many cases the natural gas signatures in near-surface samples and drill cuttings can be used to classify or predict a deeper lying source rock.

Corresponding interpretative schemes for coals, Type III kerogens and their associated hydrocarbons are progressing quickly. The shift in attention to humic sources is driven primarily by depletion of conventional oil and gas resources and the economic and societal requirements of coal and coal-bed methane.

Carbon and hydrogen isotope variations can be large for different coals and humic kerogens, particularly between the maceral groups. These isotope signatures may be diagnostic of several factors including deposit age, type, geographic location, maturity and generation history.

Aspects of the isotope systematics of humic sources and their derived hydrocarbons are presented, and a comparison with sapropelic sources is provided. A discussion of the difficulties, and some outstanding geochemical issues specific to humic sources will be included.

INTRODUCTION

The continued depletion of conventional petroleum resources, i.e. oil and natural gas resulting from the thermocatalytic transformation of hydrogen-rich, sapropelic organic matter, is renewing energy sector interest in fossil fuels derived from humic sources. Extraction of coal is an obvious alternative, but attention is increasing in the direction of natural gases associated with humic kerogens.

Rather than present a comprehensive survey of the isotope systematics associated with humic kerogens, this paper introduces specific aspects of isotope geochemistry of coals, Type III kerogens and light hydrocarbons generated from them. These isotope distributions will be placed within the more familiar context of conventional hydrocarbon-prone source rocks (e.g. marine, H-rich, sapropelic organic matter).

CARBON AND HYDROGEN ISOTOPE VARIATIONS IN ORGANIC MATTER AND KEROGEN

The stable carbon and hydrogen isotope signatures of buried organic matter are largely influenced by the environment of formation, not by the depositional setting. Figure 1, modified after Stahl (1979), illustrates the general regions of C-, H-isotope ratios occupied by terrestrial and marine higher plants, cellulose and by algae and plankton. Aquatic plants range in $\delta^{13}C_{org}$ (see note) from -13 ‰ to -27 ‰ and are typically isotopically heavier, i.e. more ^{13}C-enriched than terrestrial plants ($\delta^{13}C_{org}$ -22 ‰ to -33 ‰). At least 8 ‰ of the difference in the $^{13}C/^{12}C$ ratios between terrestrial and aquatic plants can be accounted for by differences in the precursor carbon pools. The carbon isotope ratio of atmospheric CO_2 taken up by land plants ($\delta^{13}CO_2$) ranges from -7 ‰ to -8 ‰ (Fig. 1), while the surface dissolved CO_2 used by marine plants (ΣCO_2) ranges from about 1‰ to 2.5 ‰ (dependent on temperature, latitude, primary production rates and remineralization influences).

In addition to the isotope differences in original CO_2 sources, carbon fixed through photosynthesis, one of the major primary production pathways, also has isotope distributions controlled by the isotope effects, which fractionate carbon isotopes at two stages. The first is the physical transfer of CO_2 or bicarbonate from the environment to inside the plant. For example, the velocities of gas molecules are proportional to the inverse square of their molecular weights, so that $^{12}CO_2$ (mass 44) will collide with a leaf about 1.1 % more frequently than $^{13}CO_2$ (mass 45) and hence will be taken up more frequently.

The second stage of isotopic fractionation is associated with the enzymatic fixation of carbon during photosynthesis. Again, ^{13}C is discriminated against, which leads to $\delta^{13}C_{org}$ values depleted in ^{13}C (Fig. 1). The magnitude of the depletion or isotope effect is also dependent on the photosynthetic pathway involved, i.e. the

Note: For practical reasons, stable isotope data are determined as ratios, e.g. $^{13}C/^{12}C$, rather than as absolute molecular abundances and are reported as the magnitude of excursion in permil of the sample isotope ratio relative to a known standard isotope ratio. The usual δ-notation generally used in the earth sciences is

$$\delta R_x\,(‰) = \left(\frac{R_a/R_b\text{-sample}}{R_a/R_b\text{-standard}} - 1\right) \times 10^3 \qquad (1)$$

where R_a/R_b are the isotope ratios, e.g. $^{13}C/^{12}C$ or D/H, referenced relative to the PDB or SMOW standards, respectively.

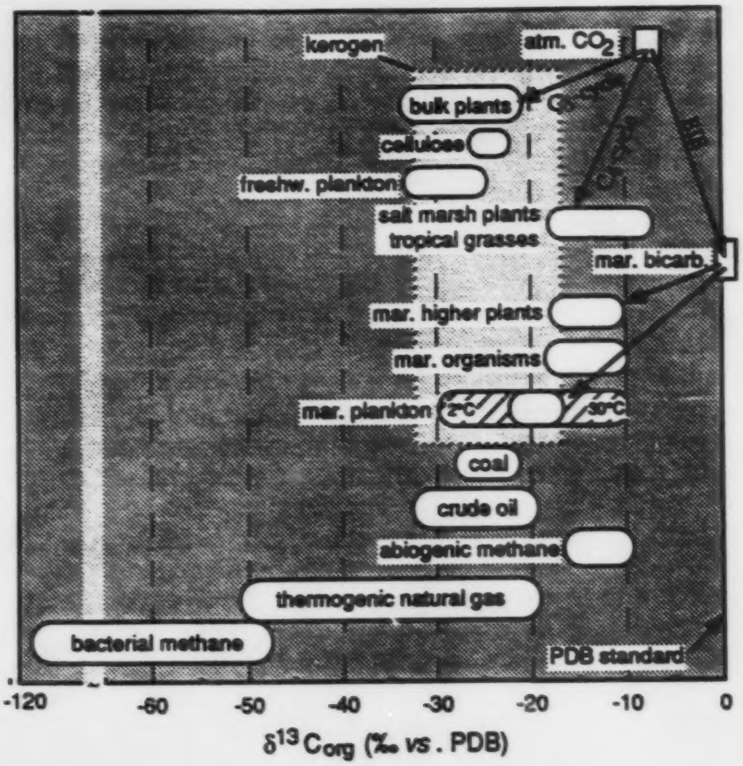

Figure 1. Range of carbon isotope ratios of major organic species within the biogeochemical cycle. $^{13}C/^{12}C$ ratios are expressed in δ-notation relative to the PeeDee Belemite (PDB) standard ($\delta^{13}C_{PDB} \equiv 0$).

Calvin cycle or C_3 plants are more effective at discriminating towards ^{12}C ($CO_2 \rightarrow C_{org} \sim -27$ ‰) than Hatch-Slack cycle or C_4 plants ($CO_2 \rightarrow C_{org} \sim -13$ ‰), e.g. Smith and Epstein (1971); Bender (1971) and DeLaune (1986). As a result of this isotope discrimination, C_3 land plants have a $\delta^{13}C_{org}$ range of -22 ‰ to -33 ‰ (mean ca. -26 ‰), whereas in C_4 plants range in $\delta^{13}C_{org}$ from -8 ‰ to -18 ‰ (mean ca. -13 ‰).

Marine phytoplankton exhibit considerable range in $\delta^{13}C_{org}$ from -10 ‰ to -30 ‰ (e.g. Eadie et al., 1978), but generally are in the range of -17 ‰ to -22 ‰. The larger isotope excursions to ^{12}C enrichment are related to colder surface water temperatures (Sackett et al., 1965). Several investigators (e.g. Abelson and Hoering, 1961) have also demonstrated a $\delta^{13}C_{org}$ dependence of phytoplankton on pCO_2 levels, i.e. greater C-isotope fractionation at higher CO_2 concentrations.

Plants exhibiting crassulacean acid metabolism (CAM) utilize both C_3 and C_4 photosynthetic pathways and their isotope signatures reflect this duality.

Biosynthesis within the plant, e.g. to lipids or cellulose, can lead to subsequent isotope partitioning as shown in Figs. 1 and 2. At the compound and intra-molecular levels (e.g. Bogacheva et al., 1980; Hayes et al., 1989), the isotope systematics and points of fractionation are complex and have been less rigorously investigated. Although outside the scope of this review, initial studies have shown that there are large and significant isotope differences between and within compounds in plant material, and that the isotope partitioning can be diagnostic of metabolic processes or environmental conditions. The new isotope ratio monitoring technique (gas chromatograph-combustion-isotope ratio mass spectrometry, Hayes et al., 1989)) should rapidly address this information shortfall.

Isotopic fractionation of hydrogen during primary production underlies similar controls to those of carbon. The isotope excursions in terrestrial and aquatic plants (range δD_{org} > 100 permil, Fig. 2) are often larger for hydrogen than carbon because the magnitude of isotope effects is greater for the former, and because of the larger range in D/H ratios of groundwaters (δD_{H2O} ca. +20 to -350 ‰ *vs.* SMOW). The data base for hydrogen isotopes of organic matter is smaller than that for carbon, but the known C-, H-isotope regions occupied by terrestrial and marine plants and their basic metabolic products (organic acids, lipids, cellulose) are presented in Fig. 2 (after BGR data base and Schoell, 1984). Fatty acids are significantly depleted in deuterium relative to humic acids and this H-isotope signal is incorporated further into the lipid fraction of organic matter (Fig. 2). The isotopic overlap for the organic acids is such that, if used singly, the C-, and H-isotopes can not distinguish between marine and terrestrial sources, but if the C-, H-isotope pairs are used in concert, then the marine or terrestrial type of environment can be roughly differentiated.

Based on limited data from the Uinta, Paris and Douala Basins (after BGR data base and Redding et al., 1980), the corresponding C-, H-isotope regions for the three major kerogen types, i.e. Type I, II, and III (after van Krevelen, 1961; Tissot and Welte, 1978), are plotted in Fig. 3. As expected, the sapropelic, hydrogen-rich, Type I kerogen has a C-, H-isotope range approaching that of the lipid fractions. Similarly, the greater proportion of lipid content in Type II vs. Type III kerogen influences their respective isotopic compositions. It is perhaps interesting to note that the isotope signature of the Type III kerogen in this data base is somewhat offset from the region known for higher plants, which would be the source of the humic matter. Furthermore, Type II and III kerogens are within a $\delta^{13}C_{org}$ range of about 5 permil, but the temperature dependence of the carbon isotope uptake and hence $\delta^{13}C_{org}$ in marine plankton creates the larger range of carbon isotope values for Type I kerogen. The isotopic zonation of kerogen types, particularly with respect to hydrogen is not well constrained at this juncture and greater variation can be expected.

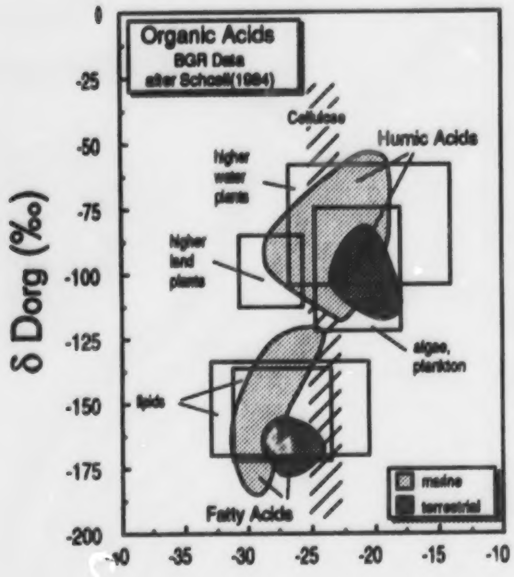

Figure 2. Carbon and hydrogen isotope characterization of marine and terrestrial plants, lipids, and cellulose. The C-, H-isotope regions for marine and terrestrial organic acids.

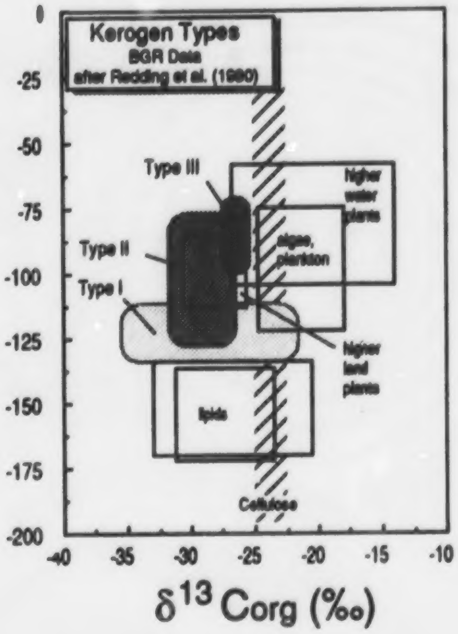

Figure 3. Differentiation of Type I, II and III kerogens with stable carbon and hydrogen isotopes.

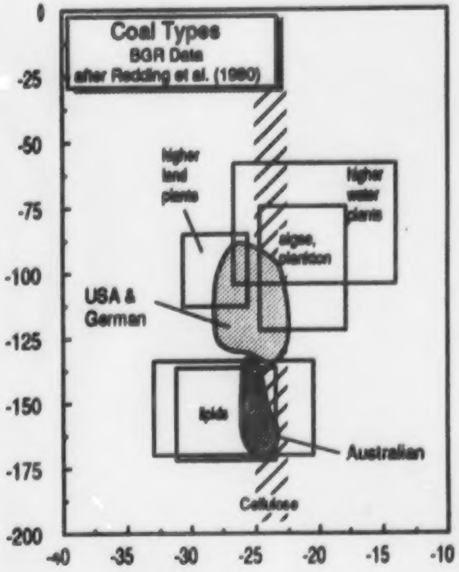

Figure 4. C-, H-isotopic zonation of coals. Gondwanan coals have distinctive isotope signature as compared with N. American or European coals.

CARBON AND HYDROGEN ISOTOPE VARIATIONS IN WHOLE COAL

CARBON

Several investigators, including Wickman (1952, 1953); Compston (1960), Redding (1978); Schwartzkopf and Schoell (1985); Holmes et al. (1991) have demonstrated that the variation of carbon isotope ratios in coals is limited to a range of about 5 permil between $\delta^{13}C_{org}$ -22 ‰ and -27 ‰ (Fig. 4). This variation is consistent for both the European/N. American-type coals and the Australian- or Gondwanan-type coals, and covers the carbon isotope range of cellulose.

Below the metaanthracite rank, the maturity of a coal does not appear to significantly influence its stable isotope ratio. This has been demonstrated by the results of Maas et al. (1978); Redding et al. (1980). At higher, metamorphic ranks a carbon isotope shift to heavier ^{13}C enriched, has been reported by McKirdy and Powell, 1974; Hoefs and Frey (1976) and Rumble et al. (1977). The lack of carbon isotope shift within the normal lignite-anthracite rank is due to the size of the carbon reservoir in coal, and the fact that the amount of carbon lost, e.g. to methane, in this maturation range is minimal, probably less than 5 % (Sackett, 1978).

To demonstrate this conclusion, Fig. 5 shows the depletion of ^{12}C from a humic kerogen or coaly source as a function of the degree of conversion to hydrocarbons. Isotopic fractionation or discrimination resulting from kinetic isotope effects can be described by Rayleigh distillation relationships. The isotope ratio of the remaining reactant pool (e.g. a generating kerogen) which is being depleted in the lighter isotope can be approximated by

$$R_r/R_o = f^{(1/\alpha-1)} \qquad (2),$$

and the progressive isotopic shift of the cumulative product pool (e.g. accumulating hydrocarbons) by

$$R_\Sigma/R_o = (1-f^{(1/\alpha-1)})/(1-f) \qquad (3),$$

where R is the isotope ratio of the initial reactant (R_o), the residual reactant at a specified time (R_r), and the cumulative product (R_Σ), respectively. The fraction of the reactant remaining is f, and α is the isotope fractionation factor for the conversion of the reactant to the product. Converting to the δ-notation for carbon isotopes, Eqs. 2 and 3 become

$$\delta^{13}C_r = \{(\delta^{13}C_o \cdot 10^3)\, f^{(1/\alpha_c-1)}\} - 10^3 \qquad (4),$$

$$\delta^{13}C_\Sigma = \{(\delta^{13}C_o \cdot 10^3)\, (1-f^{(1/\alpha_c-1)})/(1-f)\} - 10^3 \qquad (5).$$

The averaged carbon isotope fractionation factor for the conversion of coal to hydrocarbons is about 3 ‰ or an α_c of 1.003. Figure 5 shows the shift of kerogen for α_c values of 1.003, and for sensitivity comparison, α_c values of 1.001 and 1.005. The right-hand expansion in Fig. 5 shows that even a 20% conversion of the carbon in coal to hydrocarbons would shift the $\delta^{13}C_{org}$ less than 1 permil. Pyrolysis experiments by Chung (1976) and Sackett (1978) showed that the isotope fractionation associated with the methane released from the coal upon heating had α_c values of about 1.030. This value is also plotted in Fig. 5 for reference. As mentioned above, Sackett (1978) found the amount of carbon lost during this pyrolysis experimentation was less than 5 %, so that the total carbon isotope shift of coal due to methane generation would be about 1.5 permil at this conversion fraction. Thus the maturation of a coal should not produce a pronounced shift in $\delta^{13}C_{org}$.

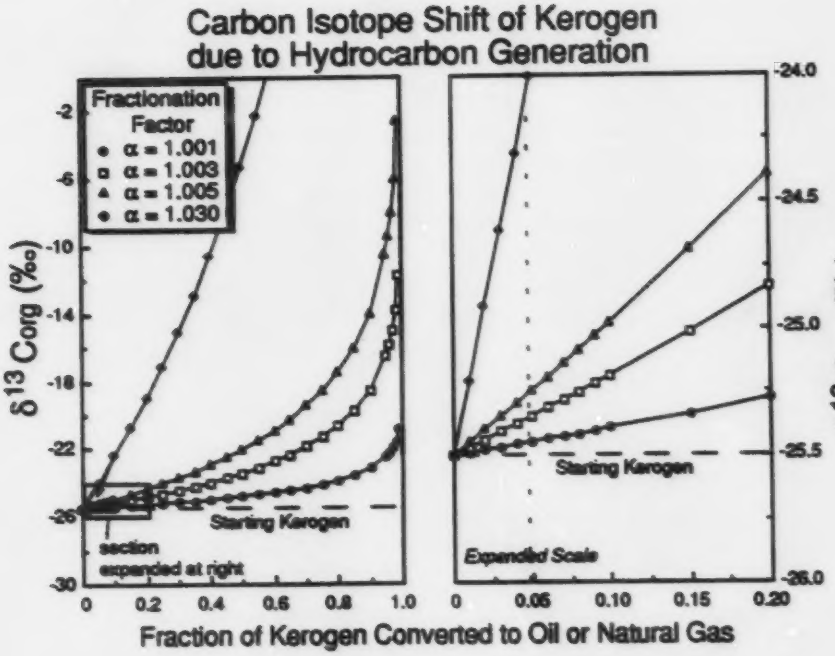

Figure 5. Theroretical shift in carbon isotope ratio of the residual organic carbon in a kerogen as a function of conversion of kerogen carbon to hydrocarbons (f = 1.0 ≡ 100% conversion). Graph on right is a scale expansion of the left-hand diagramme. Fractionation factors within the range of α_c =1.001, 1.003 and 1.005 are typical for the thermocatalytic isotope effect. The larger fractionation α_c =1.030 plotted is that known for experimental pyrolytic conversion of humic kerogen to methane.

HYDROGEN

In contrast, to the carbon isotopes, hydrogen displays a much greater range of isotope values from δD_{org} of - 75 ‰ to -175 ‰ (Fig. 4). As mentioned above and as reflected in D/H values of cellulose, this is due primarily to D/H variations in groundwater present at the time the plants were growing (e.g. Yapp and Epstein, 1977). In addition, growth conditions, such as temperature and moisture content , may influence the hydrogen isotope ratios of a coal. Figure 4 also illustrates the marked hydrogen isotopic difference between the European/N. American-type coals (mean δD_{org} of -110 ‰) and the Australian- or Gondwanan-type coals (mean δD_{org} of -140 ‰), the latter being on average about 30 permil more depleted in deuterium. Two explanations for this geographic variation between the two continental blocks have been advanced: a) differences in plant types (Scheigl and Vogel, 1970, Schoell 1984) and b) differences in climate (temperature) at the time of plant growth (Scheigl and Vogel, 1970). A geographic difference in isotope discrimination at the photosynthetic fixation stage has not been observed, but Yapp and Epstein (1977) have reported the temperature effect of hydrogen isotope fractionation.

CARBON AND HYDROGEN ISOTOPE VARIATIONS IN COAL MACERALS

As shown, bulk values of kerogen or coals provide only limited information. Distinguishing different accumulations and identifying different processes of formation or post-depositional alteration requires a more refined level of analysis. Geochemists use certain geopolymers as biomarkers to assist in characterizing the organic matter in kerogens and coals, but the technology for compound-specific stable isotope measurements is only now available (e.g. Hayes et al., 1989).

Initial work by Schwartzkopf (1984) on carbon and hydrogen isotopes of individual macerals of bituminous coals from the Ruhr Valley in Germany indicates that significant information is contained at this maceral level. Separation of the coals into the basic maceral groups (Fig.6), showed a clear isotope segregation of exinite, vitrinite and inertinite. The isotope shift was most pronounced for hydrogen isotopes but both carbon and hydrogen became enriched in the heavier isotope (^{13}C, ^{2}H) for the more refractory maceral group, i.e. $\delta^{13}C_{org}$, δD_{org} of inertinite > vitrinite > exinite. Similar results were published on maceral groups from Australian Permian coals of the Bowen and Blair Basins, including the expected Gondwana isotope-offset (Schwartzkopf, 1984). The isotope zonation is predicted from the composition of the maceral groups, but little stable isotope work has continued on the developing the interpretative value of this C-, H-isotopic distinction.

For comparison, Fig. 6 also includes the C-, H-isotope zonation of German sapropelic coals. These lipid-rich coals are further offset in both C-, H-isotope from the exinite (or liptinite) maceral group of the Ruhr Valley bituminous coals. Again, this is consistent with the isotope ratios of the dominant lipid material (Fig. 2).

The maturity dependence of the carbon and hydrogen isotope ratios of the different maceral groups has also be investigated by Schwartzkopf (1984). Figure 7 illustrates that both exinite and vitrinite become slightly ^{13}C enriched at higher rank (vitrinite reflectance range of 0.6 to 1.3 %Rm) but not in excess of the ca. 1 permil expected by the $\delta^{13}C_{org}$ shift of the whole coal in response to the maturity increase. The sapropelic coals also demonstrated this maturity dependence (Fig. 7). Inertinite showed no clear carbon isotope response to maturity.

The hydrogen isotopes of the macerals also showed no clear dependence on maturation levels. Runge (1981) suggested that isotopically heavy water (e.g. HDO) could be lost from vitrinite during the early stages of coalification and this may be reflected in the bituminous coals from the Ruhr Valley in Fig. 8.

The lack of maturity dependence of the C-, H-isotopes of macerals is favourable under some geochemical circumstances. For example, stable isotopes may be used to classify or map coal types or deposits without the added complication of maturation changes.

These represent initial results of isotope geochemistry on coals and substantial work is required to constrain this promising new approach.

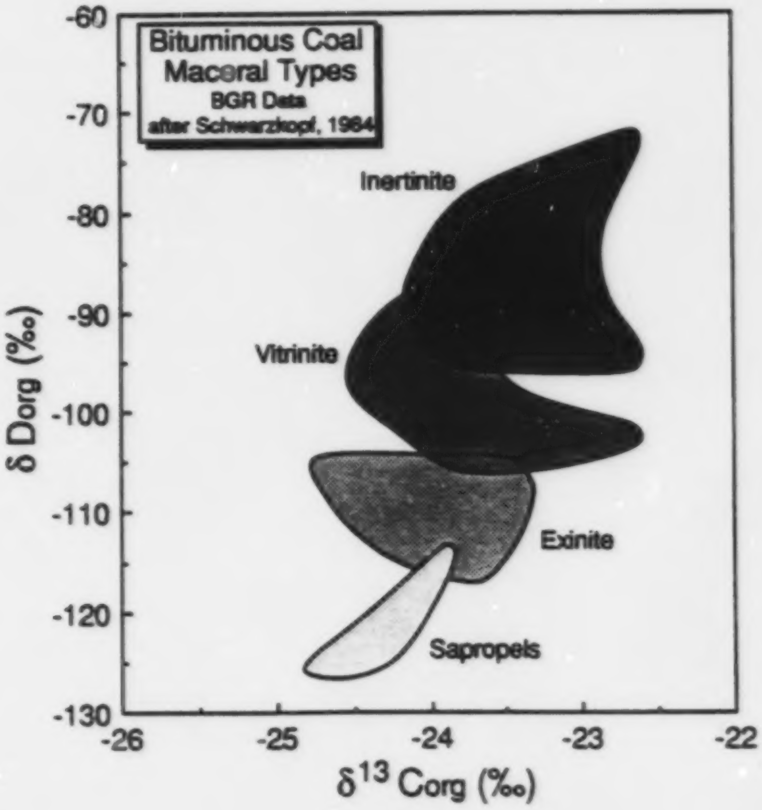

Figure 6. C-, H-isotopic segregation of different maceral groups from a bituminous coal. The C-, H-isotopic zonation of a sapropelic coal is given for comparison.

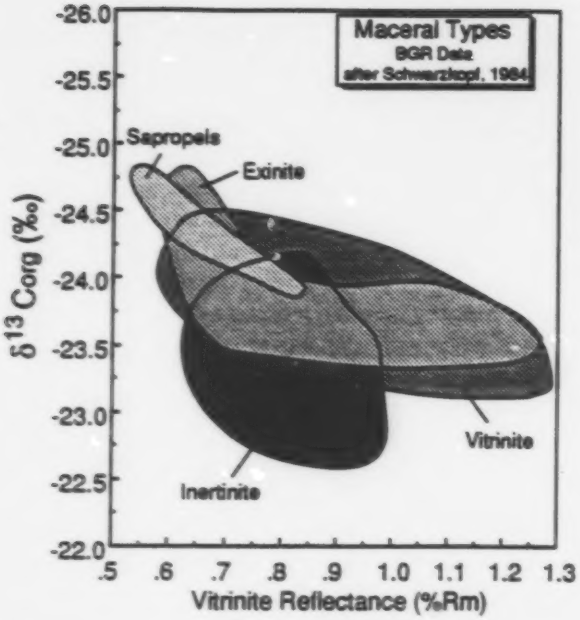

Figure 7. Dependence of $\delta^{13}C_{org}$ of individual bituminous coal macerals and a sapropelic coal on rank or level of maturity (vitrinite reflectance).

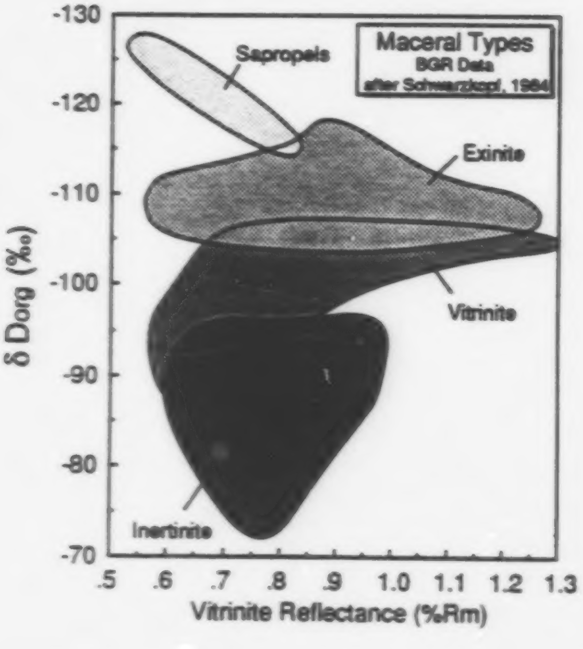

Figure 8. Dependence of δD_{org} of individual bituminous coal macerals and a sapropelic coal on rank or level of maturity (vitrinite reflectance).

CARBON AND HYDROGEN ISOTOPE VARIATIONS IN NATURAL GAS FROM TYPE III KEROGEN AND COALS

Natural gases are derived from biogenic and non-biogenic sources through diverse processes, including bacterial formation, catagenesis, hydrothermal/ geothermal activity and to an unknown degree from primordial or mantle emissions. Exploration for natural gases is aimed principally at accumulations of fossil fuel hydrocarbons, but other gas accumulations, notably noble gases can also be economic targets. Natural gas supplies about 20 % of man´s primary, external energy requirements; following the consumption of oil (38 %) and coal (30 %). Worldwide, natural gas production is currently about 1.8×10^{12} m^3/y (*c.* 65 tcf) or roughly 2 %/y of the proven geogas reserves (estimated total geogas reserves >200×10^{12} m^3, or 7×10^3 tcf).

Interest in natural gas from coals and Type III kerogens has increased dramatically during the past decade both as future energy source (e.g. coalbed methane or deep gas generation) and because of the societal and environmental concerns of the impact of methane on the atmospheric trace gas budget and global climate change. For example, the global mean methane concentration for the troposphere has risen from 1.1 to 1.8 ppmv, a rate of 1%/yr over the past 50 years (Blake and Rowland, 1988) as a consequence of increasing hydrocarbon emissions directly to the atmosphere from a variety of natural and anthropogenic sources (Whiticar, 1990).

Three categories of geochemical tools are commonly used to correlate natural gases to their sources: 1) gas concentration, 2) molecular composition and 3) stable isotope ratios. Analytical routines are frequently applied to samples from near-surface sediments/soils and seepages, cuttings from drill wells, and natural gas reservoirs.

Light hydrocarbons are the predominant compounds used to classify natural gases, but associated and co-genetic non-hydrocarbons e.g. CO_2, N_2, H_2S, He, Rn can also provide ancillary information on the source characteristics. Interpretative schemes, combining concentration and composition are founded extensively on empirical observations of natural gas occurrences. Significant, measurable and predictable differences between the various gas types provide the basis for these geochemical tools to identify and characterize primary gases, i.e. original, unaltered gases from a single source. They can also differentiate them from secondary gases, which are mixtures of different gas types or are primary gases with altered signatures due oxidation or migration. In addition to characterizing the gas type, natural gas signatures can be used to estimate the type and maturity of the organic matter or kerogen sourcing the hydrocarbons. Stable isotope ratios of the light hydrocarbons are the key and diagnostic parameters for this.

At the BGR, considerable research effort has been applied to define the stable C-, H-isotope systematics of natural gas a) formed and lost by bacterial processes (e.g. Whiticar et al., 1986; Whiticar and Faber, 1986, Whiticar, 1991), and b) generated from Type I and II kerogen by thermogenic processes (Stahl, 1977; Schoell, 1984; Faber, 1987; Whiticar, 1990). For brevity, the reader is referred these publications for a discussion of bacterial methane or conventional associated thermogenic hydrocarbons.

Coal or Type III kerogens pose some special concerns regarding the application of gas geochemistry to characterize these sources. The first is that the diagenetic conditions at the time of deposition of a peat, i.e. high organic carbon content, anaerobic, promotes vigorous methanogenesis by methyl-type fermenters. The bacterial methane can easily be retained - either sorbed or in pore space - within the deposit and be permanent part of the natural gas budget of a coal or Type III kerogen accumulation. This bacterial gas component can complicate the isotope signature of the hydrocarbons present in a coal, essentially by mixing with the thermocatalytic hydrocarbons generated at a later coalification stage.

The second complication is the sorption capacity of coals for hydrocarbons. For example, desorption of the methane from the coal during analytical procedures can be associated with an isotope effect which can influence the stable isotope signature of the natural gas. Typically, ^{12}C-methane desorbes more readily than the more strongly bound ^{13}C-methane. Sampling strategies and measurement setups must accommodate these problems.

Finally, the onset and major zone of thermogenic natural gas generation from a coal or Type III kerogen is at a higher maturity than for a corresponding Type I/II kerogen (Fig. 9). The primary product from hydrogen-poor, humic sources is methane rather than a large abundance of higher hydrocarbons.

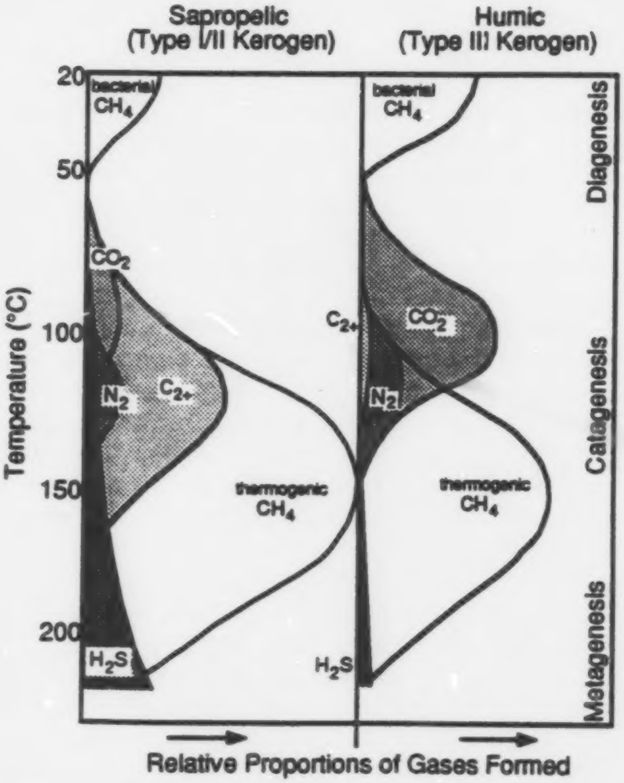

Figure 9. Comparision of natural gas generation for sapropelic (Type I/II) and humic (Type III) kerogens as a function of burial temperature. The onset of thermogenic methane formation for humic organic matter is generally later that for sapropelic sources (after Hunt 1979).

It is also important to note that once the hydrocarbons are formed, i.e. cleaved from kerogen or released from a methanogenic bacteria, the isotopic exchange with other carbon-bearing species such as water, CO_2 or kerogen is not a significant process at normal diagenetic and catagenetic conditions and times, e.g. Galimov et al. (1972); Sackett and Chung (1979). Rates of hydrogen isotope exchange are not as certain, see Kandel (1964) and Koepp, (1979), but it appears that the isotope signatures can remain intact over geologic time, provided secondary effects have not altered the isotope distribution.

Interpretative diagrammes using empirically defined molecular and isotope compositional fields have been developed by various investigators to classify natural gases. For example, Stahl, 1977 compared $C_1/\Sigma C_n$ with $\delta^{13}C_{CH4}$ to define different thermogenic gas types. Similarly, Schoell (1980) used the combination of vol $\%C_{2+}$ vs. $\delta^{13}C_{CH4}$ to distinguish, in particular for reservoired natural gases, thermally associated hydrocarbons from bacterial and humic sources. The `Bernard Diagramme´ (Fig. 10), modified after the papers of Bernard et al. (1978), and Faber and Stahl (1984), compares the molecular (vol %) ratio $C_1/(C_2+C_3)$ of a natural gas with its $\delta^{13}C_{CH4}$ value. This interpretative diagramme can be used to identify primary gases, but also those which have been altered by secondary effects such as bacterial oxidation or mixing (Whiticar, 1990). Natural gases associated with coal or Type III kerogen sources are methane rich, but can be distinguished from bacterial methane by their significantly different carbon isotope ratios (Fig. 10).

Although carbon isotope ratios of methane have been the most common isotope measurement made to classify natural gases (e.g. Colombo et al., 1965; Sackett, 1968; Silverman, 1971; Stahl, 1973; Galimov 1974), the possibility of gas mixtures in a coal, makes the measurement of hydrogen isotope ratios of methane particularly valuable.

Work by Schoell (1980) provided one of the first rigorous treatments of carbon and hydrogen isotope variations of bacterial and thermogenic hydrocarbons. This work was extended later to include information on bacterial gases as shown in the CD-diagramme of Fig. 11 (after Whiticar et al., 1986). The general zonation of C-, H-isotope signatures occupied by the various natural gas types are shown by the outlined areas in Fig. 11. The shaded regions of the diagramme outside the major gas types areas, are less common or well defined gas signatures. Natural gases evolving from Type III kerogen or coal occupy a relatively restricted region of Fig. 11, with both carbon and hydrogen isotopes of methane enriched in ^{13}C and ^{2}H compared with other conventional natural gases.

In contrast to carbon isotope ratios, the hydrogen isotope data of methane does not exhibit a clear maturity dependency, rather it provides details on the depositional environment and pathway of formation. Hydrogen isotopes are particularly useful in distinguishing methane from 1) different methanogenic pathways, 2) bacterial from early mature thermogenic gas, 3) thermogenic from geothermal/hydrothermal gas, 4) artificial or bit metamorphic sources. In these examples, methane carbon isotope ratios, if used alone, would deliver ambiguous results.

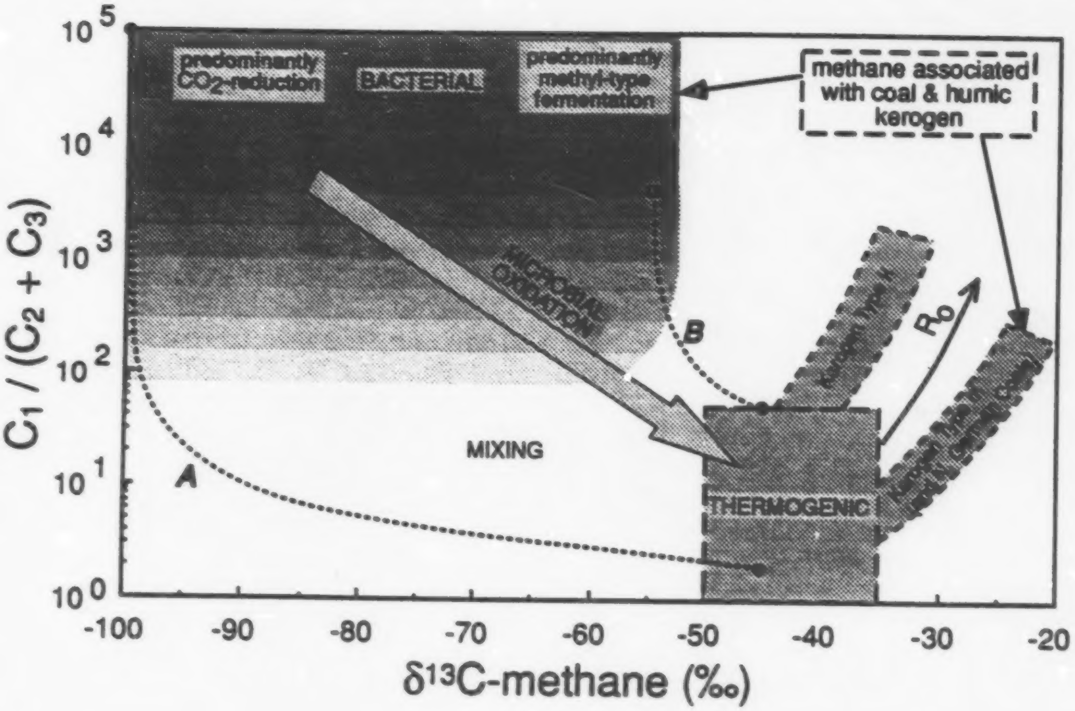

Figure 10. Bernard Diagram, to classify natural gas using the combination of molecular ratio of a natural gas $C_1/(C_2+C_3)$ (vol %) with its $\delta^{13}C_{CH4}$. (modified after Bernard, 1978 and Faber and Stahl,1984). Hydrocarbons specifically associated with humic kerogens or coal are indicated. A and B are mixing lines. The tragectory of methane oxidation is shown.

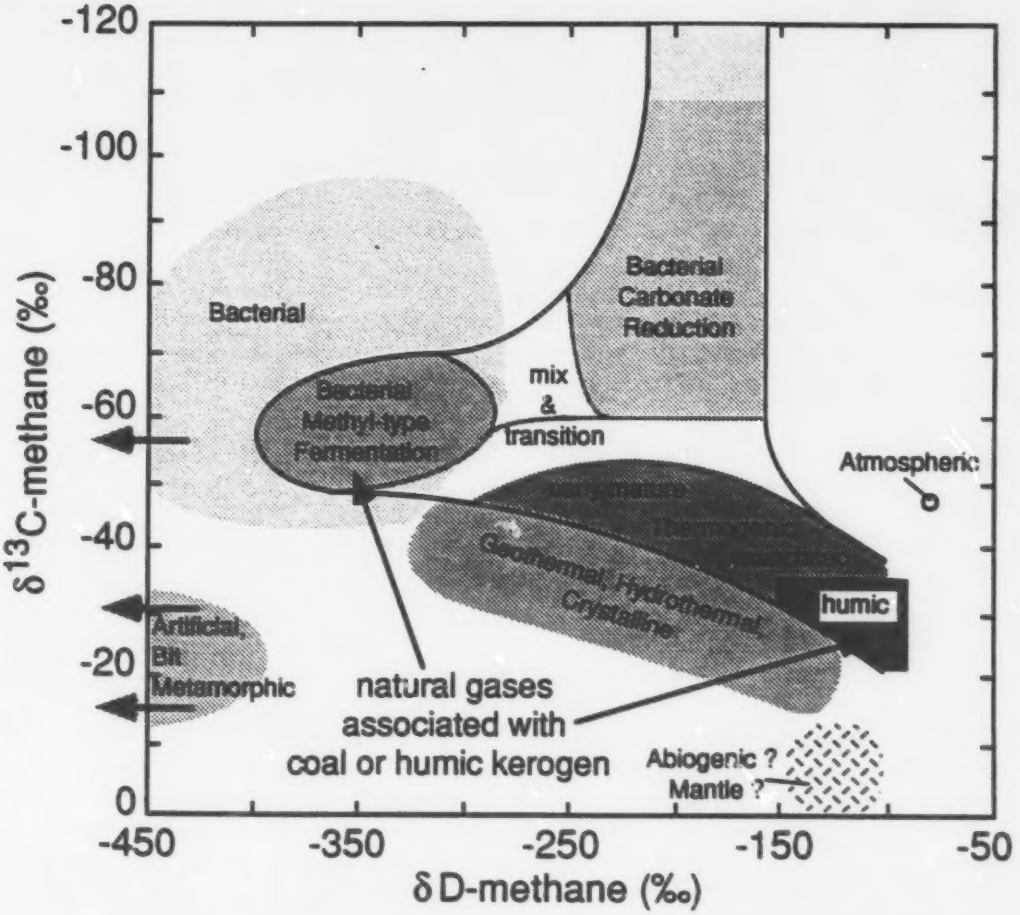

Figure 11. Combination of carbon and hydrogen isotope ratios of methane to characterize the various bacterial and thermogenic sources (after Whiticar, 1990). Natural gases contained within and derived from humic sources can be both bacterial and thermogenic depending on the burial history. The dominant isotope signatures expected are indicated, but mixing and other secondary effects can strongly influence the C-, H-isotope signals.

MATURITY ESTIMATION OF TYPE III KEROGEN WITH CARBON ISOTOPES

The relationship of carbon isotope ratios of light hydrocarbons (e.g. $\delta^{13}CH_4$, $\delta^{13}C_2H_6$, and $\delta^{13}C_3H_8$) to the maturity of the organic source from which they are derived has been developed for Type I and II kerogens (see Stahl and Koch, 1974; Faber, 1987; Whiticar, 1990). This maturity estimate is less secure for Type III kerogens. This is due to complications such as 1) only a minor portion of the kerogen will react to form hydrocarbons, 2) C_2-C_4 gas generation is limited, 3) the KIE' s are relatively small, 4) humic or coaly sources tend to retain hydrocarbons by sorption which promotes mixed gas signatures (e.g. bacterial and coal gas) and will lead to both molecular and isotopic fractionation of the hydrocarbons released, and 5) continental scale variations in coal types, e.g. from Gondwana, N. American or N. European (Schoell, 1984). Furthermore, less emphasis had been paid to characterizing light gases from Type III kerogens than for oil associated natural gases.

The methane carbon isotope maturity relationship for Type III kerogens (Fig. 12) was originally established for Upper Carboniferous and Rotliegend gases by Stahl and Koch (1974); Stahl, 1975; Boigk et al. (1976) as reported in Stahl (1977)

$$\delta^{13}C\text{-}CH_4\,(‰) = 8.6 \log_{(10)} \%Ro - 28 \qquad (6).$$

and revised by Faber (1987):

$$\delta^{13}C\text{-}CH_4\,(‰) = 13.4 \log_{(10)} \%Ro - 27.7 \qquad (7).$$

As mentioned, this relationship is less certain, particularly in the immature (%Ro < 0.7) and overmature (%Ro > 3) regions.

Using the Type III kerogen pyrolysis data of Chung and Sackett (1979), Berner (1989) modelled the isotope effects of hydrocarbon generation and estimated the 'convertible fraction' for Type III kerogen. Berner (1989) calculated an isotope fractionation factor of $\alpha_{org\text{-}hc}$ ~1.003. Berner, (1989) also compared the carbon isotope ratios of methane and ethane from NW German coal gases of Boigk et al., (1976) to the maturity of their sources and calculated the linear functions

$$\delta^{13}C\text{-}CH_4\,(‰) = 3.01\ \%Ro - 31.2 \qquad (8),$$

$$\delta^{13}C\text{-}C_2H_6\,(‰) = 3.32\ \%Ro - 25.9 \qquad (9).$$

The methane isotope relationships of Stahl (1977) and Berner (1989) are similar in trend at maturation intervals between ca 0.7 - 2 %Ro (Fig. 12) and intersect that of Faber, (1987) around 0.9 % Ro, but the former are approximately 1 ‰ lighter than Faber (1987) at maturation intervals between ca 1.5 - 3 %Ro. Carbon isotope ratios of ethane from humic kerogen is about 6 ‰ heavier than the corresponding methane, but this methane-ethane isotope separation between is much less than for a Type I/II kerogen (ca. 11‰). Substantially more data on the higher hydrocarbon homologues are need to test the dependence of ethane on maturity.

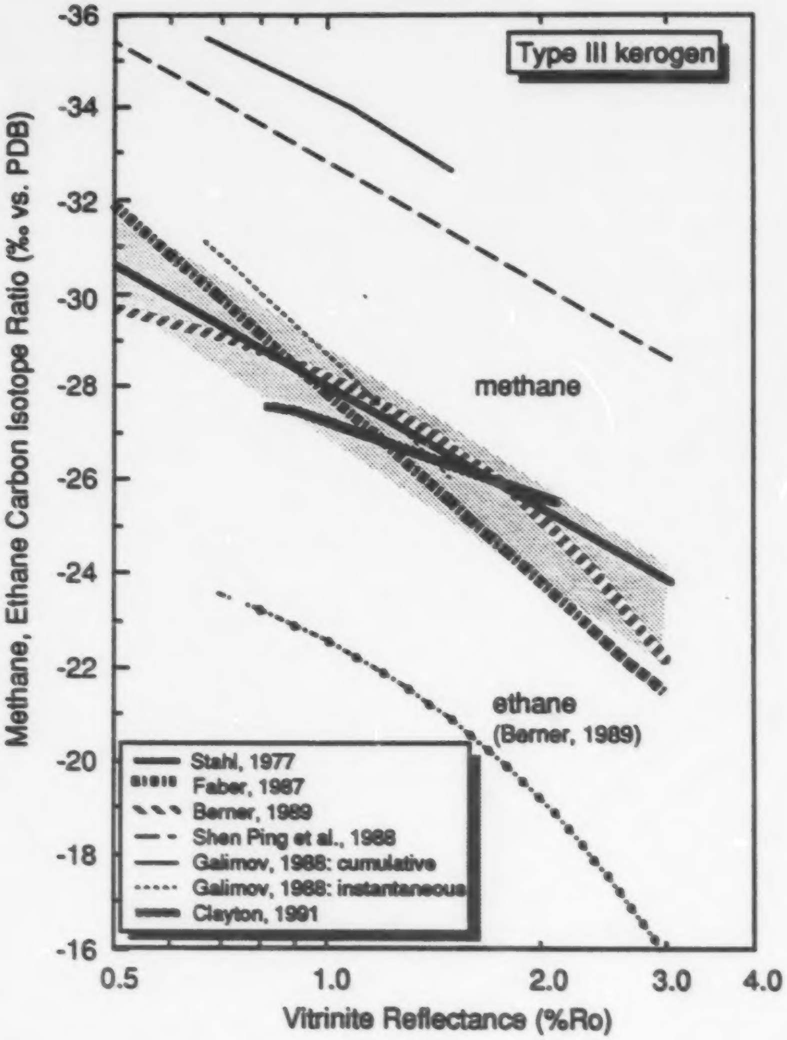

Figure 12. Dependence of stable carbon isotope ratios of methane in natural gases as a function of the source maturity (humic, Type III kerogen) from various authors and models (see text). Despite some deviation amongst the different models, the relationship between $\delta^{13}C_{CH4}$ and vitrinite reflectance can be constrained as shown by the stippled area. For comparison, the maturity dependence of $\delta^{13}C_{C2H6}$ for Type III kerogen (Eq. 9, Berner, 1989) is also shown.

Clayton (1991) extended the ideas of Berner (1989) by relating the $\delta^{13}C-CH_4$ of Boigk et al., (1976) to a production index and a maturity equivalent (Fig. 12). His $\delta^{13}C-CH_4$ - %Ro relationship is also similar to those reported by the previous authors.

Shen Ping et al., (1988) reported a $\delta^{13}C-CH_4$ - %Ro relationship from humic kerogens of the Sychuan Basin in China:

$$\delta^{13}C\text{-}CH_4 (‰) = 8.64 \log_{(10)} \%Ro - 32.8 \qquad (10)$$

Figure 12 shows that the methane carbon isotope data from their sample set are considerably offset from those of the other authors. The explanation for this large difference is not apparent, but several possibilities have been discussed above.

Galimov (1988) took a somewhat different approach and used the activation energies for the generation of methane from different structural positions of humic organic matter to estimate the shift in $\delta^{13}C-CH_4$ as a function of the degree of reaction (maturity). The two $\delta^{13}C-CH_4$ - %Ro relationships generated by Galimov (1988), shown in Fig. 12, depend on whether the methane isotope signature is an integrated value based on the accumulation of the gas generated (cumulative) or if the signature is only that of the latest methane generated (instantaneous). Galimov's instantaneous curve roughly follows the empirical curves of Stahl (1977); Faber (1987) and Berner (1989), but the response of $\delta^{13}C-CH_4$ to maturity is greater for the instantaneous curve than the calculated response by Clayton (1991). The cumulative curve of Galimov is lighter by about 5-6 permil compared with the empirical lines, but appears to agree with the relationship of Shen Ping et al., (1988).

Although an approximate maturity estimate can be made, substantial additional effort is required to understand the carbon isotope - maturity relationship for Type III kerogen before it can be routinely applied to hydrocarbon exploration or recovery strategies.

Adapting the interpretative scheme for sapropelic kerogen (Faber 1987, Whiticar, 1990), Berner (1989) calculated the methane-ethane relationship for Type III kerogens, based on Eqs. 8 and 9, to be

$$\delta^{13}C\text{-}CH_4 (‰) = 0.91\ \delta^{13}C\text{-}C_2H_6 (‰) - 7.7 \qquad (11).$$

Fig. 13 shows the comparison of carbon isotope ratios of methane vs. ethane for hydrocarbons generated from humic sources. Points of iso-maturation (% Ro) are indicated on the figure. As the degree of maturation increases for the single humic source, the $\delta^{13}C-CH_4$ and $\delta^{13}C-C_2H_6$ ratios will follow along Eq. 11. Departures from co-lineararity are a strong indicator of secondary effects such as the admixture of a bacterial gas or of a different thermogenic gas (as shown in Fig. 13). Methane oxidation would also shift the methane-ethane isotope pair off the line because methane is preferentially consumed by bacteria, and the microbial uptake is associated with an isotope effect which enriches the residual methane in ^{13}C (Whiticar and Faber, 1986).

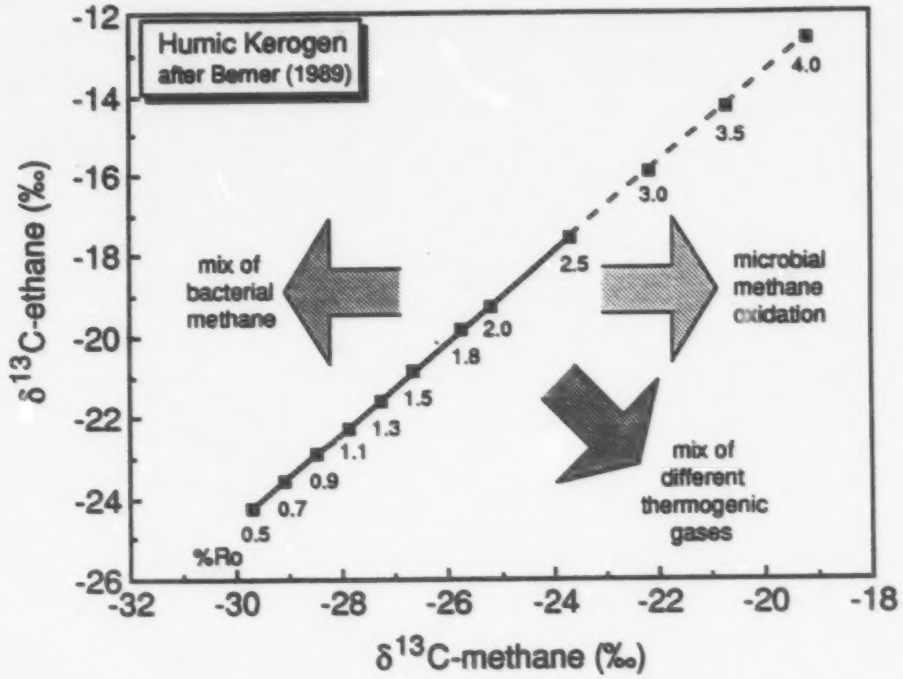

Figure 13. Relationship of stable carbon isotope ratios for co-genetic methane vs. ethane in a natural gas from a Type III kerogen according to Eq. 11 (based on Eqs 8 and 9). Gases falling off the expected relationships are usually not primary and may represent secondary effects such as mixing of bacterial or different thermogenic gases, or microbial oxidation of methane. Vitrinite reflectance equivalents are given for reference.

CONCLUSIONS

Humic kerogens and coals can be reliably characterized by geochemical tools available to determine their molecular and stable isotopic compositions. In particular, the new approcaches and applications with stable isotope emphasized in this paper, particularly at the maceral and compound level, greatly improve the interpretative precision over whole coal techniques. Significantly more work is needed in this area to define the stable carbon and hydrogen isotope systematics.

Geochemical tools are also in place to classify natural gas types, but the characterization of natural gases evolving from humic kerogen and coal remains problematic. This is due primarily to the high retentive capacity of organic-rich deposits for light hydrocarbons, and the probability of mixtures of gases from different sources in the deposit. Improved methods of gas extraction from coals and humic kerogens remain to be developed to enable representative hydrocarbon samples to be obtained.

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2

COAL INDUSTRY PAPERS AND ABSTRACTS

NOTES

AIR POLLUTION CONTROL BY APPLICATION OF *AGLOFLOAT PROCESS FOR CLEANING HIGH SULFUR BITUMINOUS COALS

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ABSTRACT

Modified oil agglomeration process for the beneficiation of high-ash and sulfur bituminous coal has been developed and tested at the Alberta Research Council. This process, named Aglofloat*, has been evaluated in a laboratory scale and in the continuous operation using 5 k/h and 250 kg/h testing facilities. Further development of this technique into demonstration, and subsequenty commercial scale will contribute to the reduction of air pollution from utilization of low quality thermal coals.

INTRODUCTION

The main emphasis of current pollution control regulations is placed on air pollution control requirements and is focused on controlling the man-made atmospheric pollutant emissions.

Most of the air pollutant emissions are generated by the combustion of coal in industrial coal-fired plants and power stations. These emissions are in the form of solids (particulates) and gases (sulfur dioxide-SO_2 and nitrogen oxides - NO_x). Particulates and sulfur dioxide emissions are caused by utilization of high-ash and sulfur coals. Particulates arise from the ash-forming constituents of the coal and any unburnt carbon and are carried out with the flue gas as a fly ash. The particulate limits currently applied to industrial coal-fired plants range from 35 to 615 mg/m^3 varying with the country of origin and plant size[1]. Depending on a type of combustor, the uncontrolled particulate emissions can be as high as 1000 mg/m^3 to 20000 mg/m^3 which requires 50% to 98% particulate removal to meet the regulations.

The man-made emissions of the compounds containing sulfur into the atmosphere account for 60% of all emissions on a global scale. About 90% of the total sulfur released is emitted as sulfur dioxide (SO_2), 82% of which is derived from combustion of high-sulfur coals or other fossil fuels.

Current standards for SO_2 emissions from industrial coal-fired plants, established by different countries in an effort to limit the deterioration of ambient air quality, range from 400 to 2400 mg/m^3 which corresponds to the coal sulfur content in the range 0.25% to 1.25% [1].

A wide range of approaches can be used to control both of these emissions. Besides switching to low-ash and sulfur coals, which is subject to their availability and transportation cost, several technologies are being developed to make it possible to utilize high-ash and sulfur coals in a compliance with emission standards. These technologies fall into the following categories:

- The physical removal of pyritic sulfur prior to combustion
- The use of fluidized-bed combustion with limestone additions
- The removal of sulfur oxide from the combustion flue gas
- The conversion of high-sulfur coal to a clean fuel by such processes as liquefaction-gasification or chemical extraction.

The simplicity, efficiency and cost-effectiveness of these technologies are the major criteria that will determine the viability and the future of our most abundant domestic fuel, coal. One of the coal cleaning technologies having the potential to meet these criteria is a modified oil agglomeration technology which has been developed at the Alberta Research Council in cooperation with U.S. Electric Power Research Institute. Being classified as pre-combustion physical cleaning method, the Aglofloat® process is capable of removing ash- and sulfur-forming minerals that are not chemically bound and can be liberated from coal matrix by comminution. This process utilizes the difference in the hydrophobic nature of coal and mineral surfaces. Now-polar liquids, such as hydrocarbons, added to an agitated coal-water slurry, preferentially cover the surface of coal particles. Due to the collisions caused by mixing, these particles coalesce and form agglomerates which can be easily separated from the minerals suspended in water phase. Initially, oil agglomeration was found to be not very efficient in pyritic sulfur removal due to hydrophobic tendencies of coal pyrite and some entrainment effects [2]. Modification of the process procedure in a way of using small quantities of the bridging oils in combination with the well controlled agglomeration step and extensive washing of the product allowed to improve the process performance in terms of mineral matter and particularly pyritic sulfur rejection.

The Aglofloat® process has been evaluated in a laboratory scale and subsequently in the continuous operation using the testing facilities of 5 kg/h and 250 kg/h capacities. The distinctive feature of the continuous systems was the utilization of pyrite separator that resulted in additional removal of pyritic sulfur.

In this paper, the results of the Aglofloat® process for deashing and desulfurization of different coal feedstocks are discussed.

Experimental

1. Batch Testing

Schematic representation of the Aglofloat® procedure is given in Fig. 1. The batch testing has been developed into single- and two-stage procedures and their detailed description was given earlier [3]. A typical single-stage procedure includes grinding of coal sample to a top size of 600 μm, preparation of coal-water slurry and coal microagglomeration with heavy oil-based bridging liquid under a vigorous agitation. Due to the differences in surface properties between organic and inorganic parts of coal resulting in their differential affinity to bridging oils, redistribution of the phases occurs. Three phase coal/water/oil system is transformed into two phase microagglomerates/aqueous mineral matter suspension system. The next step includes separation of formed microagglomerates by flotation followed by washing procedure. In the two-stage procedure, the same steps are repeated except for the addition of interstage wet grinding of the separated microagglomerates before sending them to a washing step.

Experimental procedures and conditions used in the batch-scale testing are described in Table 1. Properties of tested coals are presented in Table 2.

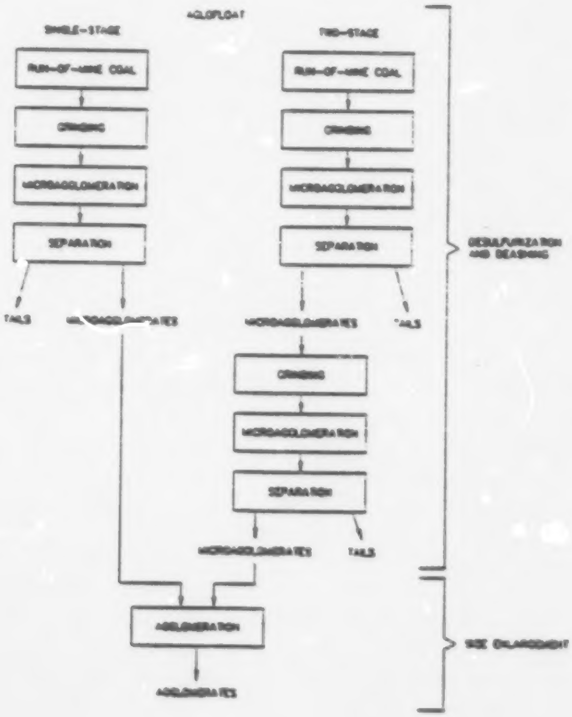
AGLOFLOAT
SINGLE-STAGE
TWO-STAGE
RUN-OF-MINE COAL
GRINDING
MICROAGGLOMERATION
SEPARATION
RUN-OF-MINE COAL
GRINDING
MICROAGGLOMERATION
SEPARATION
DESULFURIZATION AND DEASHING
TAILS
MICROAGGLOMERATES
MICROAGGLOMERATES
TAILS
GRINDING
MICROAGGLOMERATION
SEPARATION
MICROAGGLOMERATES
TAILS
AGGLOMERATION
SIZE ENLARGEMENT
AGGLOMERATES

Figure 1: Beneficiation of High-Ash and Sulfur Coals by Aglofloat/Agglomeration

Table 1. Aglofloat Process Conditions - Batch Scale

Process Conditions	Single-stage	Two-Stage
Coal Particle Size	600 μm x 0 (28 mesh x 0) d_{50}=150, 100 & 75 μm (100, 150 & 200 mesh) D_{50} ~150 μm is preferred	600 μm x 0 (28 mesh x 0) d_{50} ~ 150 μm (100 mesh) ↓ 150 μm x 0 (100 mesh x 0) d_{50} ~40 (325 mesh)
Bridging Liquid Type	Mixture of heavy oil and diesel or diesel	Mixture of heavy oil and diesel or diesel
Bridging Liquid Consumption (based on dry coal)	0.5% to 1.5%	1% to 3.0%
Solids Concentration (based on dry coal)		
Agglomeration:	10%-25%	10%-25%
Flotation:	5%-12.5%	5%-12.5%
Temperature	Ambient	Ambient
pH of Slurry	Natural	Natural

Table 2. Properties of Tested Coals*

Sample	Ash [%]	Sulfur [%]		Calorific Value [Btu/lb]	lbs $SO_2/10^6$ Btu
		Total	Pyritic		
Run-of-mine coals					
Illinois No. 6	39.5	4.19	2.33	8,350	9.75
Pittsburgh	17.0	4.98	2.70	11,962	8.32
Kentucky No. 9	14.6	5.09	3.09	12,430	8.21
Upper Freeport	12.3	2.33	1.37	13,560	3.43
Precleaned coals					
Indiana V	9.7	3.77	1.83	13,270	5.68
Devco thermal	5.7	2.30	1.88	14,500	4.00
Prep. Plant Streams					
Cyclone overflow - bit.	19.2	1.13	0.58	12,240	1.81
EPA Standard					
U.S.					1.2
Can					0.6

*All values on dry basis.

2. Continuous System - 5 kg/h

The first step in the development of the Aglofloat® process resulted in the design and construction of the continuous unit with the capacity of 5 kg/h. The process performance has been tested for two different system configurations. The first system, schematically shown in Fig. 2, consists of slurry preparation circuit, high-shear agglomeration tank and the flotation tank. A distinctive feature of this system is the addition of hydraulic separator where, under the specific conditions, the high density pyrite and ash rich particles carried over with the froth are separated and removed as a reject.

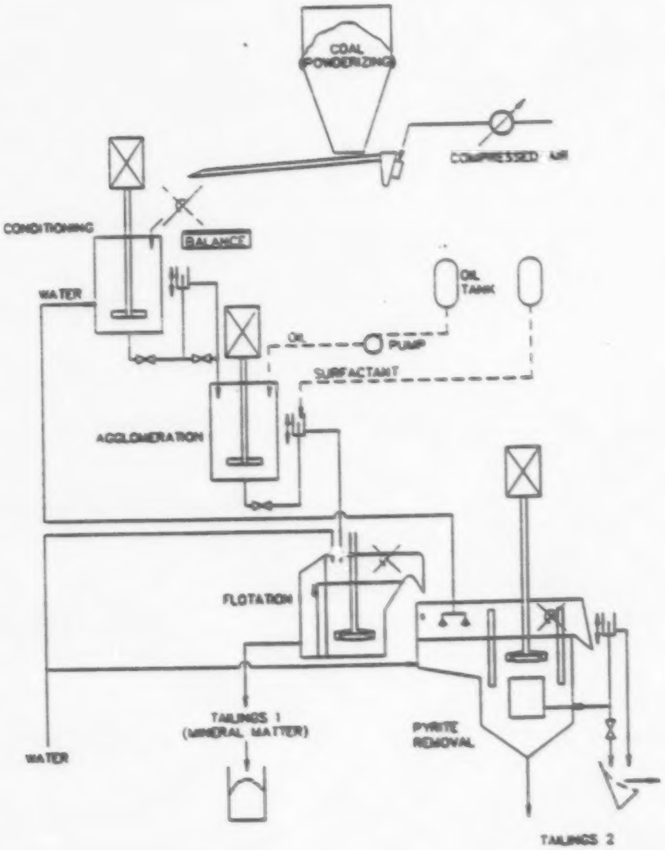
COAL
(POWDERIZING)
COMPRESSED AIR
CONDITIONING
BALANCE
WATER
OIL
TANK
OIL
PUMP
SURFACTANT
AGGLOMERATION
FLOTATION
TAILINGS 1
(MINERAL MATTER)
PYRITE
REMOVAL
WATER
TAILINGS 2

Figure 2: Small Continuous Unit - 5 kg/h (System 1)

The second system, shown in Fig. 3., utilizes a flume pyrite separator as a replacement for the flotation cell. The flume separator is equipped with a spiral feeder, spray washers and has four stationary settling zones for pyrite and ash collection and removal.

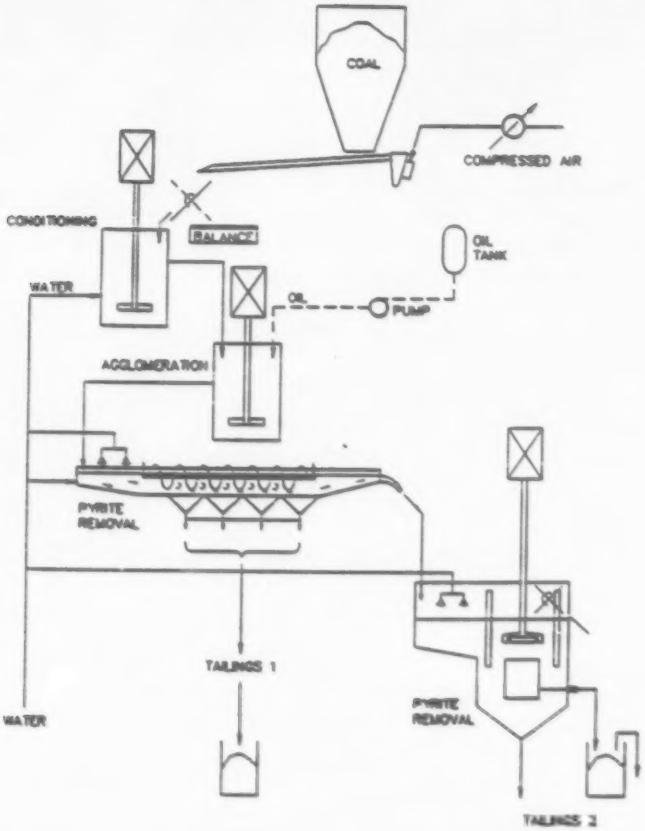
COAL
COMPRESSED AIR
CONDITIONING
BALANCE
OIL TANK
WATER
OIL
PUMP
AGGLOMERATION
PYRITE REMOVAL
TAILINGS 1
WATER
PYRITE REMOVAL
TAILINGS 2

Figure 3: Small Continuous Unit - 5 kg/h (System 2)

3. Continuous System - 250 kg/h

The next scale-up step of the continuous Aglofloat® process has led to the construction of the Integrated Agglomeration Test Facilities (IATF) with the capacity of 250 kg/h. The IATF included all major equipment required for various process configuration, as shown in Fig. 1, with the exception that the grinding equipment for primary and secondary coal crushing was added in front of the system, and a double-decker screen dewatering equipment at the end. The block diagram of the IATF unit is shown in Fig. 4. The advanced froth cleaning section and low-shear agglomeration section are the integral parts of the continuous system. However, they are the optional configurations that can be bypassed in case if an enhancement in ash and pyrite removal is negligible as compared to the main configuration efficiency, and in case if the production of enlarged agglomerates is not required.

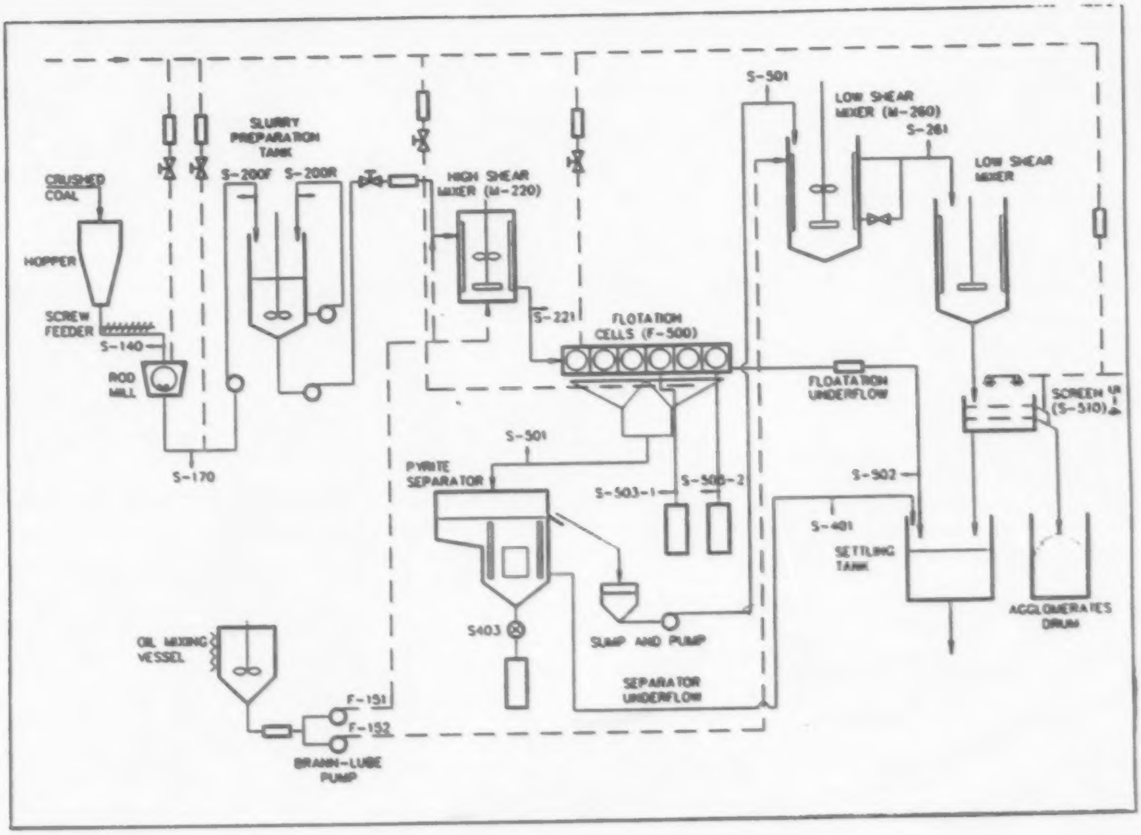
CRUSHED COAL
HOPPER
SCREW FEEDER
S-140
ROD MILL
S-170
SLURRY PREPARATION TANK
S-200F
S-200R
HIGH SHEAR MIXER (M-220)
S-221
FLOTATION CELLS (F-500)
S-501
LOW SHEAR MIXER (M-260)
S-261
LOW SHEAR MIXER
FLOATATION UNDERFLOW
SCREEN (S-510)
S-501
PYRITE SEPARATOR
S-503-1
S-503-2
S-502
S-401
SETTLING TANK
S403
SUMP AND PUMP
AGGLOMERATES DRUM
OIL MIXING VESSEL
F-151
F-152
SEPARATOR UNDERFLOW
BRANN-LUBE PUMP

Figure 4: Large Continuous Unit - 250 kg/h

Results and Discussion

1. Batch Studies

Run-of-mine, channel and precleaned coal feedstocks as well as the conventional preparation plant streams were extensively tested using both single- and two-stage Aglofloat® processes.

These coal samples were characterized by various levels of ash and sulfur, and a pyritic sulfur component could represent as much as 65%-70% of the total sulfur balance. Sulfur dioxide emissions from utilizing some of the coals would exceed the standard U.S. and Canadian levels by eight to sixteen times respectively.

Experimental results, presented in Table 3, demonstrate that significant rejection of ash and sulfur can be achieved for any type of coal or processed stream by application of the Aglofloat® process, although the extent of the removal varies with the coal origin and type.

For run-of-mine coals, the ash removal efficiency reaches 52% to 86% by application of the two-stage procedure which indicates up to 20% increased efficiency over the single stage. The inorganic sulfur rejection by two-stage process range from 70% to 84% and it is on the average 20% to 30% higher than that of the single-stage process. It translates into about 45% reduction in SO_2 emission. For the precleaned coals, the results of ash and inorganic sulfur rejection are 45%-53% and 52%-60% respectively. They are usually lower than those received for run-of-mine coals and reflect partial removal of minerals during the conventional precleaning prior to agglomeration. Very good ash and sulfur removal is achieved for cyclone overflow from the Homer City Coal Cleaning Plant. Both results exceed 70% with 92.1% combustible recovery. This suggests that the Aglofloat® process can also be very efficient for the recovery of coal fines from various preparation plant streams.

Table 3. Beneficiation of High-Ash and Sulfur Coals by Aglofloat® Process*

Process Feedstock	Ash %	Total S %	Performance				
			CMR %	AR %	TSR %	ISR %	lbs SO_2/ 10^6 Btu
Run-of-mine coals							
Illinois No. 6	39.5	4.19	-	-	-	-	9.75
Single-stage	10.6	4.31	93.3	78	14	58	6.75
Two-stage	6.8	3.62	89.2	86	28	80	5.41
Pittsburgh	17.0	4.98	-	-	-	-	8.32
Single-stage	7.2	3.88	92.1	64	33	51	5.71
Two-stage	5.4	3.26	88.4	73	45	70	4.71
Kentucky No. 9	14.6	5.09	-	-	-	-	8.21
Single-stage	6.8	3.62	94.5	60	39	60	5.33
Two-stage	4.4	2.81	93.8	75	54	84	4.04
Upper Freeport	12.3	2.33	-	-	-	-	3.43
Single-stage	8.9	1.67	97.4	32	33	49	2.35
Two-stage	6.6	1.22	96.1	52	53	80	1.67
Precleaned coals							
Indiana V	9.7	3.77	-	-	-	-	5.68
Two-stage	5.8	3.14	97.6	45	23	42	4.63
Devco Thermal	5.7	2.90	-	-	-	-	4.00
Two-stage	2.9	1.90	94.3	53	40	60	2.54
Prep. Plant Streams							
Cyclone Overflow-bit.	19.2	1.13	-	-	-	-	1.81
Single-stage	5.8	0.78	92.1	76	45	78	1.04

*All values on dry basis.
CMR - coal matter recovery
AR - ash rejection
TSR - total sulfur rejection
ISR - inorganic suflur rejection

2. Continuous System with Capacity 5 kg/h

Several bituminous coals have been subjected for continuous Aglofloat® processing. The tests conducted with run-of-mine Upper Freeport coal, characterized by moderate ash and sulfur contents, have been selected to present the process performance and effectiveness. The results of these tests are presented in Table 4. The batch results are also included for the comparison.

Table 4. Cleaning of Upper Freeport Coal in 5 kg/h Continuous System

Test	Coal Cap. (kg/h)	Oil Add. (%)	Initial Coal		Product			Sulfur Reduction		Coal Matter Rec. (%)
			Ash (%)	Total S (%)	Ash (%)	Total S (%)	Pyr. S (%)	Total (%)	Inorg-anic (%)	
System 1										
Run 1	4.60	1.9	13.0	2.17	8.5	1.54	0.61	33	61	-
Run 2	3.80	2.2	13.0	2.17	8.2	1.57	0.67	32	58	-
Run 3	5.14	2.4	12.2	2.30	8.4	1.55	0.67	36	54	95
Run 4	2.16	6.2	12.2	2.30	9.5	1.70	0.72	28	50	94
System 2										
Run 1	5.37	2.2	16.5	2.27	9.6	1.36	0.47	44	64	92
Run 2	5.85	2.3	16.5	2.27	9.5	1.26	0.39	49	70	92
Batch System- Single-stage-		0.6	12.3	2.33	8.9	1.67	0.80	33	49	97

*All values on dry basis.

Analysis of the results revealed quite a significant difference in the performances of the two systems, especially in terms of sulfur reduction. In System 1, the clean coal ash content ranges from 8.2% to 9.5% and inorganic sulfur reduction from 50% to 62%. Such fluctuations are caused by the variation in bridging oil addition which is in agreement with the previous findings [4]. With the decrease of the bridging oil addition, the product ash content decreases and the sulfur removal increases. The result of single-stage batch processing in terms of sulfur removal (49%), appears to be lower than those obtained in the continuous, more sophisticated systems. The higher percentage of sulfur removal in the continuous System 1 in contrast with the batch test suggests that incorporation of the hydraulic pyrite separator into the process circuit improves the cleaning efficiency of the process for about 15%. The better performance of System 2 in terms of sulfur removal can be explained by better efficiency of the flume pyrite separator over the flotation cell. The spray washers provide fresh water supply and intensive throughout washing of the froth, while slow motion of the froth by means of the spiral feeder allows sufficient time for the pyrite particles to be settled in four collecting zones. An additional 5%-10% pyrite removal can be expected by using System 2, however some loss of combustibles has to be taken into account. The ash removal doesn't seem to be affected by switching from System 1 to System 2. The slightly higher values for product ash in System 2 (9.5%, 9.6%) are most likely derived from higher feed ash value (16.5%). Both systems perform in good agreement with the single-stage batch process performance for ash removal.

3. Continuous System with Capcity of 250 kg/h

The optimization and evaluation of 250 kg/h continuous agglomeration system was carried out with run-of-mine Illinois No. 6 coal. The test objectives were to examine the equipment performance, to optimize the Aglofloat® process and to determine the efficiency of a base and optional circuit configurations. The process conditions and feedstock analysis are presented in Table 5, while the test results along with the batch and small continuous unit (5 kg/h) results are depicted in Table 6.

Table 5. Cleaning of Run-of-Mine Illinois No. 6 Coal Feedstock Analysis* and Process Conditions

Test	Oil Addition	Feed Coal	
		Ash [%]	Total S [%]
Batch			
Single-stage	0.5	34.8	4.82
Two-stage	1.0	34.8	4.82
Small Unit (System 1)	2.46	32.8	5.18
Run 1	2.22	32.5	5.05
Run 2	2.49	32.3	5.02
Run 3			
Large Unit			
Run 1	0.75	31.4	4.67
Run 2	0.6	35.2	4.51

*Dry basis

Table 6. Beneficiation of Run-of-Mine Illinois No. 6 Coal by Aglofloat® Process Using Different Systems

Test	After Flotation				After Pyrite Separator				Combust-ible Recovery
	Product		Sulfur Reduction		Product		Sulfur Reduction		
	Ash [%]	Total S [%]	Total [%]	Pyr. [%]	Ash [%]	Total S [%]	Total [%]	Pyr. [%]	[%]
Batch									
Single-stage	11.8	4.31	34	49	—	—	—	—	94
Two-stage	9.1	4.04	40	58	—	—	—	—	92
Small Unit (System 1)									
Run 1	15.4	4.71	27.8	40	9.93	4.09	41.5	66	77
Run 2	14.0	4.64	27.1	45	9.90	4.03	45.0	69	73
Large Unit									
Run 1	10.8	3.87	29.4	44	11.2	3.71	30.5	59	78
Run 2	10.9	4.09	27.6	49	13.8	4.03	32.6	55	79

The comparison of the two continuous systems of 5 kg/h and 250 kg/h capacities, with the batch scale performance reveals that both continuous units generate acceptable scale-up factors for the process. In terms of sulfur removal, the efficiency of the base configuration (flotation for microagglomerate recovery) for both continuous systems is comparable with the single-stage batch test results. The pyritic sulfur reductions for batch - 5 kg/h - 250 kg/h systems are 49%, 40% to 45% and 44% to 49%, respectively. The process efficiency for the optional configuration (with the pyrite separator) is comparable with the two-stage batch performance. However, the recovery of coal matter is lower in the continuous operations. The pyritic sulfur reduction for batch two-stage process is 58% and 59%-55% for the large continuous system. Hence, it can be concluded that up to 10% increase in pyrite cleaning efficiency can be expected by switching to optional process configuration. An additional 30% to 40% ash reduction is also observed in this case. The results, obtained with the small 5 kg/h continuous unit are slightly higher in terms of pyrite reduction as compared to the large unit results.

Conclusions

Based on the above mentioned results the following conclusions are made:

1. For run-of-mine bituminous coals, the first testing level (batch) experiments demonstrated 52% to 86% ash removal efficiency and 70% to 84% inorganic sulfur removal. For precleaned coals, the corresponding results were 45% to 53% and 42% to 60% respectively. As a result, the SO_2 emission potential has been reduced by about 45% for most of the coals bringing it closer to the level required by EPA standards. This reduction would significantly reduce the cost of more expensive but still required post-combustion flue gas desulfurization.

2. Scale-up of the Aglofloat® process to 5 kg/h and 250 kg/h continuous operations allowed to demonstrate the commercial potential of the process and addressed the key technical and economic issues. Two system configurations have been tested in 5 kg/h unit. The results showed that 10% to 15% higher cleaning efficiency over the single-stage batch process could be achieved in System 1 (with hydraulic pyrite separator) and additional 5% to 10% improvement was observed by switching to System 2 (with flume separator). Results from 250 kg/h system were in agreement with the batch test results in terms of sulfur removal, but at lower coal matter recovery. Addition of pyrite separator into the process circuit improved the cleaning efficiency of the system by 10%.

Acknowledgements

The authors wish to acknowledge the funding of this work by the Alberta Research Council (ARC)/Electric Power Research Institute (EPRI) Consortium on "Coal Processing Development Program". The support of all the Canadian and American members of the Consortium is greatly appreciated.

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WESTAR MINING'S BALMER OPERATIONS COAL QUALITY CONTROL

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Westar Mining's Balmer Operations has operated in the southeast corner of British Columbia for over 20 years. During this time over 100 million tonnes of clean metallurgical coal has been produced, mostly from the 15 meter thick Balmer 10 seam.

In the past five years mining has uncovered up to fourteen complex upper seams along with the Balmer 10 seam and mining has spread over five lower ratio pit areas. Difficulties in maximizing coal recovery and optimizing quality control have been addressed during this transition to multi-seam mining. The operation is now faced with an increasing strip ratio lower plant yields and an aging equipment fleet. These factors along with an eroding financial position due to unfavourable coal pricing and a strong Canadian dollar have left Balmer with a significant challenge to remain competitive.

Balmer is focusing on things we have control over by revising our 15 year long range plan to increase efficiencies. Alternate pits within the large coal reserve area were evaluated to define the most economic new mining areas and large pits using large equipment was decided on P & H 4100 and XPA2800 shovels matched with 4D Haulpak 240 tonne trucks will enable Balmer to lower unit costs while moving 48 million BCM's of waste and producing 6 million tonnes of clean coal annually.

The Balmer engineering department has implemented changes to achieve the targeted productivities. Restructuring of the department has provided seven day coverage in engineering, geology, survey and blasting. Better integration of long-term and short-term planning is giving better guidance to mine operations. Inovations to improve coal flow have included a computerized truck dispatch system, overland raw coal conveyor and on-stream raw and clean coal ash analyzers. Using an updated computerized coal simulator, raw coal blends are optimized to maximize plant feed, yield and clean coal quality. Improved communications between the mine, plant and port will ensure a more consistent product to Balmer's customers.

NOTES

WASHABILITY OF PEACE RIVER AND EAST KOOTENAY COALS

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ABSTRACT

This study is concerned with the washability characteristics of British Columbia coals from different seams, geological formations, coalfields and regions. Classical washability parameters were used together with the washability number and degree-of-washing parameters to analyze the data. Special emphasis was put on comparing the washability numbers between coal seams, as this parameter appears to be a better indicator of ease of washing of a coal seam. It defines the boundary between free mineral matter and mineral matter intergrown with coal. It also gives a scale of difficulties associated with cleaning, to a specific clean-coal product.

Coals discussed in this paper are from two major British Columbia coalfields: the northeast or Peace River area and the southeast or East Kootenay area (Figures 1 and 2. Due to complex geological conditions in both regions, local changes in coal quality are quite common. Variations are not only within the formation, but also among the individual seams. Therefore, using washability numbers for comparison is even more desirable, as they provide a single numeric measure of the variation.

INTRODUCTION

The washability of any particular coal seam is directly related to the amount and type of mineral matter associated with the coal matter (macerals). The mode of association is a result of the sedimentation conditions that prevailed during formation of the coal seam. Coal seams have their origin in peat-forming swamps and marshes. These swamps and marshes are formed from different plant communities, each having its own set of biological and geochemical conditions. Mixtures of macerals and minerals are formed in these environmentally distinct areas. The individual ecosystems control the formation and composition of different layers within the coal seam, referred to as lithotypes.

The compositional characteristics of lithotypes control the coal quality within the seams. Many physical, chemical and mechanical properties of coal are governed by the lithotype composition (Jeremic, 1980; Falcon and Falcon, 1987; Hower et al., 1987; Hower, 1988; Hower and Lineberry, 1988). Stratigraphically, each seam represents a separate sequence of lithotypes, with specific coal quality in terms of type and grade.

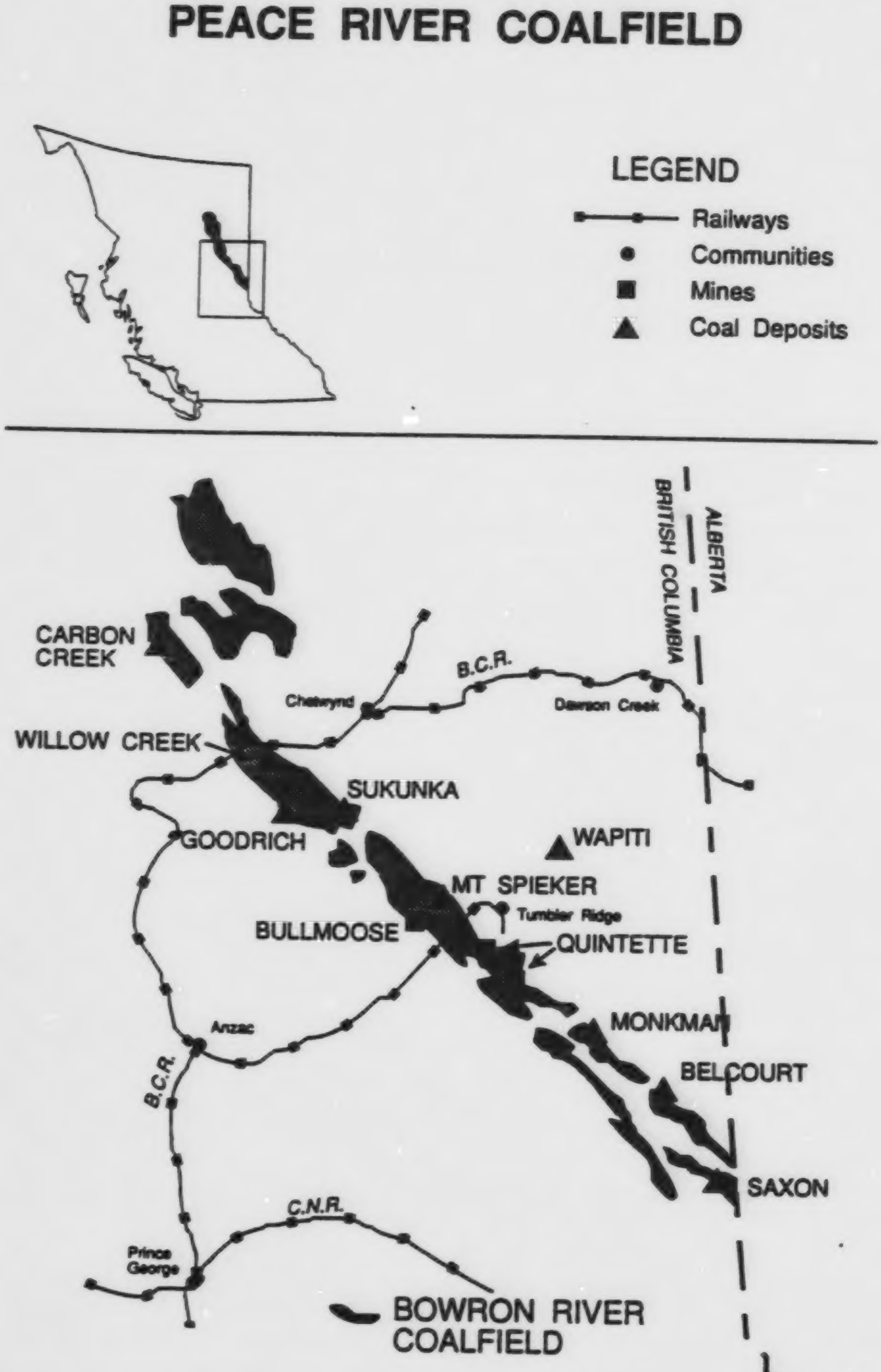
PEACE RIVER COALFIELD
LEGEND
Railways
Communities
Mines
Coal Deposits
ALBERTA
BRITISH COLUMBIA
CARBON CREEK
B.C.R.
Chetwynd
Dawson Creek
WILLOW CREEK
SUKUNKA
GOODRICH
WAPITI
MT SPIEKER
Tumbler Ridge
BULLMOOSE
QUINTETTE
MONKMAN
BELCOURT
Anzac
B.C.R.
SAXON
C.N.R.
Prince George
BOWRON RIVER COALFIELD

Figure 1. Coal deposits and location of mines in the study area; Peace River coalfield of northeast British Columbia.

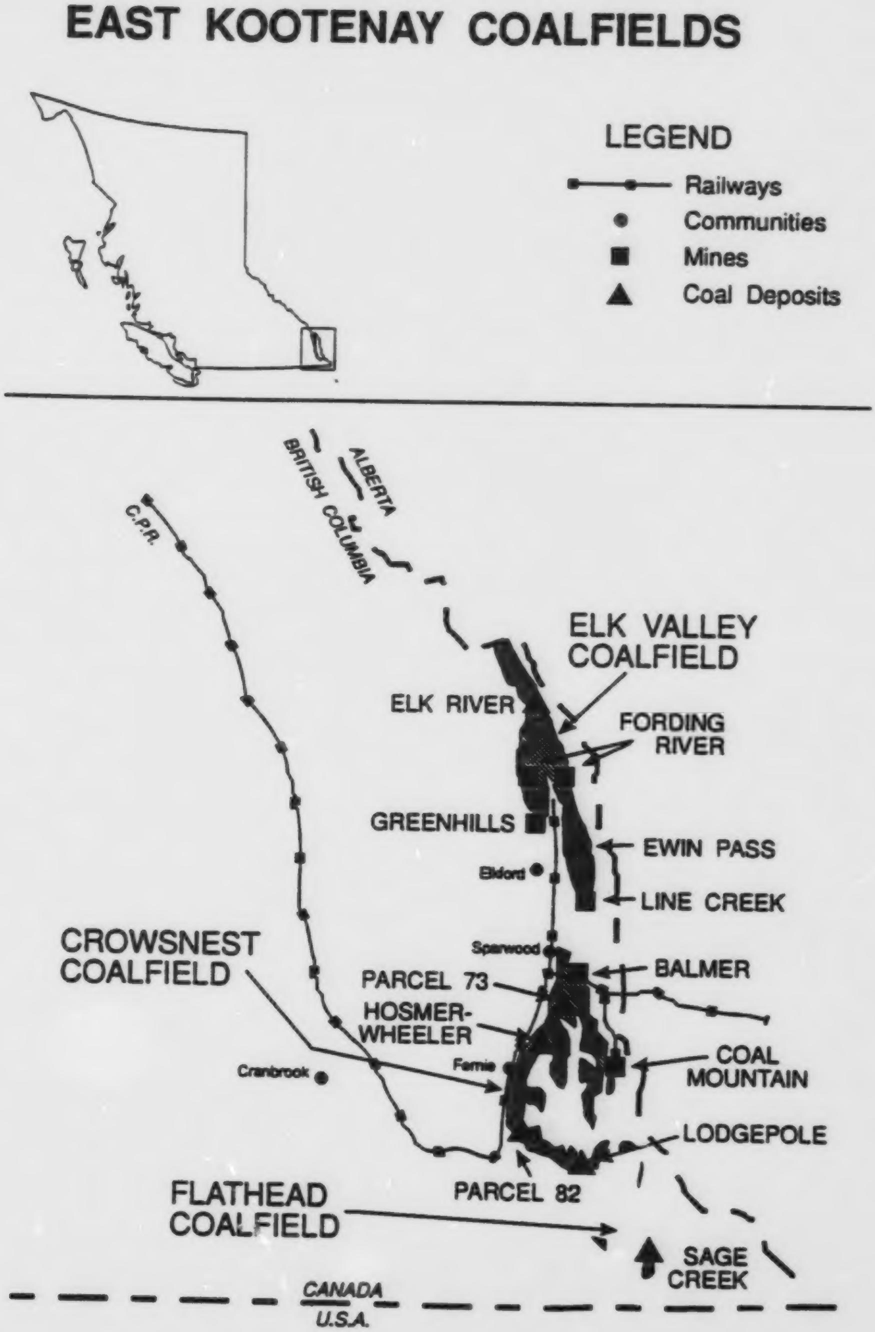
EAST KOOTENAY COALFIELDS
LEGEND
Railways
Communities
Mines
Coal Deposits
ALBERTA
BRITISH COLUMBIA
C.P.R.
ELK VALLEY COALFIELD
ELK RIVER
FORDING RIVER
GREENHILLS
EWIN PASS
Elkford
LINE CREEK
Sparwood
CROWSNEST COALFIELD
BALMER
PARCEL 73
HOSMER-WHEELER
Fernie
Cranbrook
COAL MOUNTAIN
LODGEPOLE
PARCEL 82
FLATHEAD COALFIELD
SAGE CREEK
CANADA
U.S.A.

Figure 2. Coal deposits and locations of mines in the study area; East Kootenay coalfield of southeast British Columbia.

From the washability point of view, the important aspects of coal quality are the amount and type of mineral matter found within the coal seam. The variation in mineral matter content is not only due to the association of macerals with minerals (lithotypes), but also due to mining methods, which may result in out-of-seam dilution. This effect, however, is reflected in a lower yield of clean product from a given seam.

An important factor in coal quality variability is folding and faulting of seams, resulting in sheared coal. Shearing leads to increased friability of coals and results in a disproportionate amount of fines and poor washability characteristics (Bustin, 1982), as is the case in many of the coal-bearing formations in western Canada. The poor washability of sheared coals is especially evident when the shearing plane is close to the contact of a seam. This results in dissemination of comminuted floor or roof rock through the coal, as pointed out by Bustin (1982), and difficulty arises in distinguishing and separating sheared rock from the coal seam.

The ease of washing, as traditionally measured by yield of clean coal, amount of near-gravity material and other washability parameters, is not always the best measure of the intrinsic character of a particular coal seam (Sarkar and Das, 1974; Sarkar et al., 1977; Sanders and Brooks, 1986; Holuszko and Grieve, 1990). For example, clean coal yield is strongly influenced by the amount of out-of-seam dilution. Furthermore, yield-ash and density-yield relationships are coal dependent, and cannot be reliably used to compare washability of various coal seams, especially if the coals are of different origins.

The introduction of washability number by Sarkar (1977) made it possible to classify and correlate coal seams in accordance with their inherent washability characteristics. The washability number appears to be the only parameter not affected appreciably by any large increase in extraneous mineral matter in the raw coal. When used in conjunction with other washability parameters it becomes a very useful tool to assess the ease of washing of coal.

OBJECTIVES

The aims of the project are three fold:

- to compile available washability data and create a computer database file for future use.

- to analyze the data in order to look for relationships between the washability characteristics and other inherent properties of coal, such as its rank and type;

-to accomodate washability parameters such as washability number and degree of washing into the new classification system (Alpern et al., 1989) as an alternative to the yield of clean coal at preselected ash levels. Yield of clean coal is a purely technical term used to describe the final product and does not reflect the natural characteristics of coal.

After compiling washability data from various British Columbia coalfields it became possible to compare washability characteristics of coal seams from different regions. The comparison of the two major coal producing coalfields, Peace River and East Kootenay, is the subject of this paper.

GEOLOGICAL SETTINGS

Coal deposits in the Peace River and East Kootenay regions produce all of the metallurgical coal in the province. The coal measures lie within the Rocky Mountain Front Ranges and Foothills of British Columbia. The northeast British Columbia (Peace River) coalfield contains coals of Early and Late Cretaceous age, whereas the coal deposits in the southeast (East Kootenay) are of Jurassic-Cretaceous age. Coal-bearing strata throughout the region were deposited in deltaic and alluvial plain environments. Tectonism associated with the mountain building has resulted in strongly faulted and folded coal measures. The coals are mainly medium to low-volatile bituminous in rank, and are generally very suitable for good quality coke (Smith, 1989).

Peace River Coalfield

Coal deposits of the Peace River coalfield are found within the northern inner foothills belt, which extends northwestwards for more than 300 kilometres from the Alberta - British Columbia border east of Prince George (Figure 1). The coal deposits occur in four different geological formations, but the major coal measures of the region are in the Early Cretaceous Gething Formation of the Bullhead Group and Early Cretaceous Gates Formation of the Fort St. John Group. The Gates Formation contains 70 per cent of commercially attractive coal measures (Smith, 1989). Coals of the Jurassic-Cretaceous Minnes Group and the Late Cretaceous Wapiti Formation are generally considered as economically unattractive.

Structurally, the area is characterized by folding and thrust faulting, resulting in thickening of some of the coal seams. The least structural deformation is observed in the coal seam in the Wapiti Formation. In terms of coal quality, most of the seams in the region are classified as medium volatile with excellent coking characteristics and low sulphur, usually less than 1 per cent. The rank of coals in the Gates and Gething formations is in the range from high-volatile A to low-volatile, whereas the Wapiti Formation coal is of much lower rank, high-volatile C.

Early Cretaceous Gates Formation seams are characterized by relatively low vitrinite and high inertinite contents with negligible liptinite (Lamberson et al., 1991; Marchioni and Kalkreuth, 1991). The lithotype composition of coal seams is highly variable, reflecting various depositional conditions during peat formation. In some seams banded lithotypes are predominant, in others brighter lithotypes are the most abundant, but generally banded lithotypes are characteristic of the Gates coals. The dull appearance of some lithotypes is due either to the presence of mineral matter, or an abundance of inertodetrinite and mineral matter, particularly quartz (Marchioni and Kalkreuth, 1991) or close proximity to clastic partings. According to Lamberson et al. (1991) differences in lithotype stratigraphy are due to variations in ground-water level as well as differences between wetland types. These lithotypes represent a continuous change in depositional environment from forest swamps (dry and wet) to dry herbaceous or shrubby marshes.

Coal seams from the upper part of Gething Formation are in general composed predominantly of bright lithotypes. The reported maceral analysis for these seams has shown that they are rather low (66%) in vitrinite content and high in inertinite macerals, mainly semifusinite and micrinite. The mineral matter content is exceptionally low. The carbonate minerals (mostly calcite) occur in cleats and fill cavities in semifusinite and fusinite; clays occur more rarely and are associated with massive vitrinite (Cook, 1972).

The coal at the base of the Late Cretaceous Wapiti Formation is the only seam in this formation with possible economic potential. It contains a great deal of mineral matter both from the dirt bands (partings) and inherent in the coal.

East Kootenay Coalfield

The coal-bearing strata in southeast British Columbia are confined to the Mist Mountain Formation of the Jurassic-Cretaceous Kootenay Group. Mist Mountain coals are between high and low-volatile bituminous rank (Smith, 1989). Coal beds comprise 8 to 12 per cent of the stratigraphic thickness of the formation (Grieve, 1985). Coal seams in the lower part of the formation tend to be thicker and more continuous, and in some instances structural deformation has resulted in substantial thickening of seams (Grieve, 1985; Smith, 1989).

Structural deformation of coals in the Mist Mountain Formation has tremendous impact not only on the mining methods used but also on the coal quality. Faulting and folding have created many problems in terms of correlation of the seams, and in many cases discontinuity of the seams has complicated mine planning and development. The quality of coal has been deteriorated as a result of shearing (Bustin, 1982).

Petrographic composition of the Mist Mountain coals varies from inertinite-rich to vitrinite-rich, from base to the top of the formation (Cameron, 1972; Grieve, 1985). This reflects a systematic variation in depositional environments, changing from an upper to a lower delta plain (Cameron, 1972). In terms of lithotype composition this is reflected by a brightening-upward (increasing in bright lithotypes) tendency in these coals.

SAMPLE SELECTION FOR WASHABILITY STUDY

Washability data for bulk samples from across the province were compiled from the Ministry's collection of coal exploration assessment reports. Data from the southeast and northeast coalfields were chosen for comparison here, as the majority of commercially producing seams are found in these two coalfields. Economically, the most significant coal seams are in the Gates and Mist Mountain formations, therefore, the study was limited to seams in these formations. For a list of samples see Table 1.

Table 1. List of properties representing Peace River and East Kootenay coalfields.

PEACE RIVER		EAST KOOTENAY	
Bullmoose	non-attrited	Balmer	attrited
Belcourt	non-attrited	Elk River	non-attrited
Quintette	attrited	Ewin Pass	attrited
Mount Spieker	non-attrited	Ewin Creek	attrited
Sukunka	attrited	Fording	attrited
Wapiti	non-attrited	Greenhills	non-attrited
		Horshoe Ridge	non-attrited
		Line Creek	attrited

The following criteria for sample selection were applied:

- only bulk samples representing run-of-mine coal were used;

- a limit was imposed on ash content of raw coal to avoid biases caused by out-of-seam dilution; only samples with ash content of less than 35 per cent were considered;

- the washability data of attritted samples were preferred to the data on crushed samples (the non-attritted sample data were used when in accordance with the particular coal preparation plant practice);

- samples do not necessarily represent the whole coalfield; they are rather considered to be representative of the seams which are contributing to coal production within the studied regions;

- a restriction was also imposed on the top-size of the samples; the upper limit of the top-size was restricted to maxima of 150 and 50 millimetres; a lower size limit of 0.50 millimeter was uniform for all the samples;

- crushed samples were used for the liberation studies; in these tests the washability of the coal at a larger top-size was compared with the same coal crushed to significantly lower sizes.

METHODS

To compare washability characteristics of different coal seams, the following **washability parameters** were used: yield of clean coal curve, corresponding yield of rejects, and the near-gravity material-distribution curve. For convenience of comparison seams from both coalfields were assigned to categories according to the yield of their clean coal product at 10 per cent ash. These categories were as follows: yield of clean coal in the range of **90 to 100** per cent; **70 to 90** per cent; and **less than 70** per cent.

A statistical approach was used to determine the number of seams from each of the coalfields falling into the different categories.

The degree of washing (N) and washability number (W_n) were also used to further examine the inherent washability characteristics of coal seams. The degree of washing at any specific gravity cut-point is expressed as follows:

$$N = w(a-b)/a$$

where:

a - the ash content of the raw coal (feed)

b - the ash content of the clean coal at a given density of separation

w - the yield of clean coal at a given density of separation

For a given coal, depending on the rank, type and mineral matter associated with it, there will always be a density of separation which will yield the most of the cleanest product possible. The optimum degree of washing (N_{opt}) is then obtained by plotting degree-of-washing values (N) versus the density of separation, and finding the maximum value. Degree-of-washing plots were constructed for three yield-of-clean-coal ranges.

The ash content of the clean coal at the optimum degree of washing has specific significance in characterizing the coal. Therefore, it is advisable to express the value of the degree of washing as the ratio to the clean-coal-ash at this optimum level (Sarkar and Das, 1974; Sarkar et al., 1977; Sanders and Brooks, 1986). The washability number can be expressed as follows:

$$W_n = 10(N_{opt}/b_{opt})$$

where:

b_{opt} = ash content at N_{opt}.

The degree of washing and washability number take into account not only the ash content of the raw coal but also yield and ash of clean coal. The washability number describes the inherent washability characteristics of a coal far better than any of the classical washability parameters. The washability index was first introduced by Sarkar and Das (1974) to outline patterns of depositional conditions of Indian coal seams. In other studies, using the washability number as the comparative measure was recommended (Sarkar et al., 1977; Sanders and Brooks, 1986).

For the present study, the washability numbers were calculated for the arbitrarily devised yield-of-clean-coal categories. This allowed comparison of the coal seams falling into the same range in terms of yield of clean coal at the selected ash level (10% ash) from different regions.

RESULTS

The washability results discussed in this paper are not considered to represent the final coal product quality from the studied areas. They are an attempt to make comparisons between various coal seams and find a way of predicting the changes in washability characteristics in relation to various geological conditions.

Yield of Clean Coal and Quality of Rejects

The clean-coal curve plotted as cumulative ash content at any given density of separation, versus cumulative yield, predicts the theoretical yield of clean coal at a given ash level. This is a strictly technical parameter which has a major influence on the economics of the mined seam. However, comparable yields of clean coal at a preselected ash level may be obtained with varying different degrees of difficulty, due to varying inherent coal characteristics. Clean-coal curves were plotted for a number of seams from the two coalfields. The Peace River coalfield was represented by 24 seams from three geological formations. The majority of seams, however, are from the Gates Formation. The East Kootenay coalfield was represented by 35 seams from Mist Mountain Formation. These seams were assigned to different categories according to their yield of coal product at 10 per cent ash, and clean-coal curves were plotted in the corresponding ranges for seams from both coalfields (Figure 3).

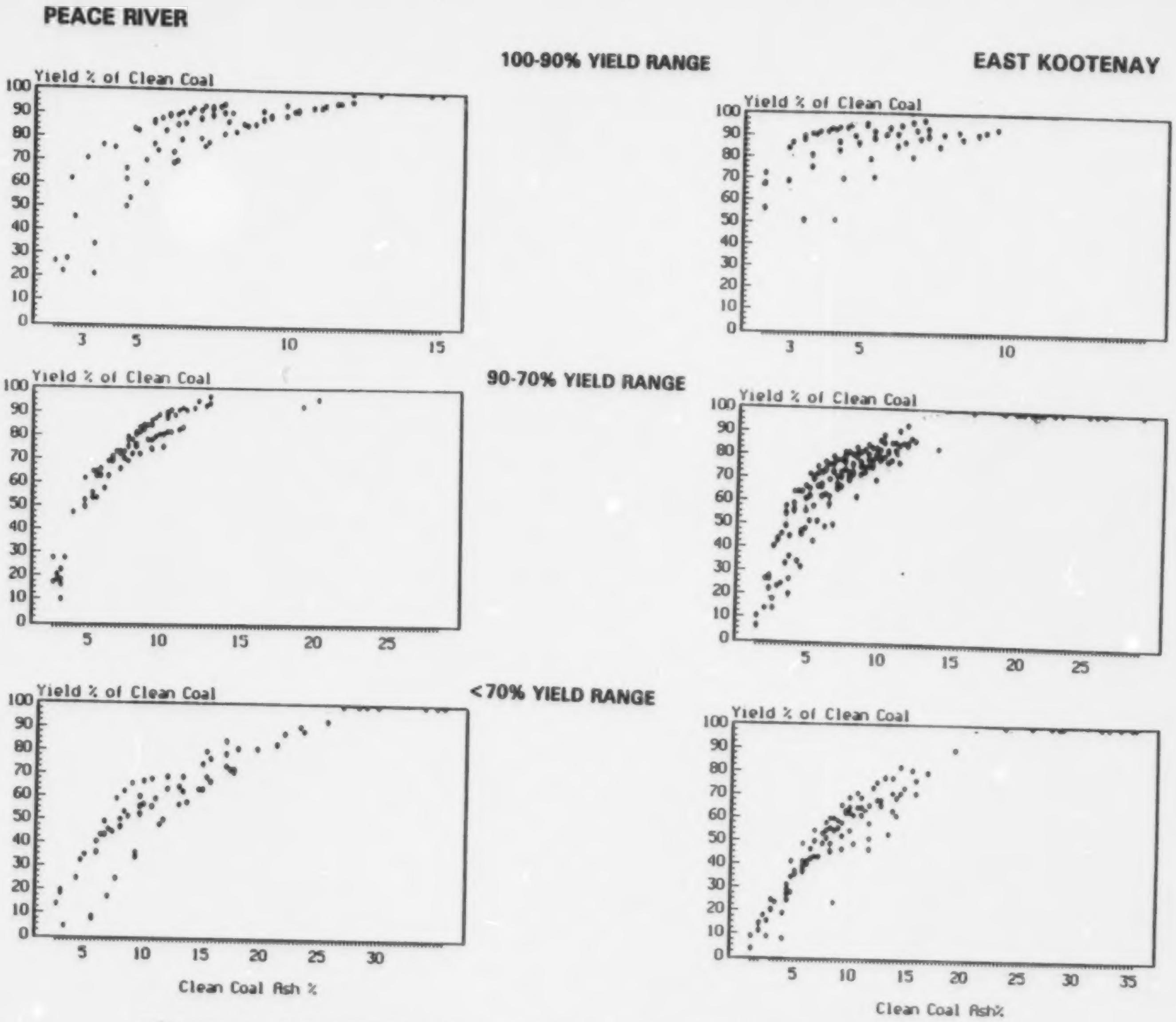

Figure 3. The ranges of variation for cumulative clean coal curves for seams falling within specified yield ranges from Peace River coalfield and East Kootenay coalfield.

For coals from the Peace River coalfield, eight seams out of twenty four were in the range of 100 to 90 per cent yield at 10 per cent ash, nine seams were in the second highest range, 90 to 70 per cent yield at 10 per cent ash, and the remaining were assigned to the lowest range. The raw ash as well as the top-size of the samples from both coalfields is reported in Table 2.

For the seams representing East Kootenay coalfield only six out of thirty five examined fell into the high yield category, eighteen were in the middle range, and eleven were in the lowest yield range. The ranges of ash content and top-size of the raw coal samples from both coalfields are also given in Table 2.

The clean-coal curves within three ranges of yields for both regions, show quite a wide range of coal characteristics. This is particularly noticeable for the high-yield range for both formations. Similarly, the quality of rejects varies significantly for seams in the same yield category. The cumulative-reject curves for different categories of clean-coal yield for seams from the two coalfields are shown in Figure 4.

There is no consistent trend between the yield categories of the seams studied and their stratigraphic position in the Gates Formation sequence. For the Mist Mountain Formation, seams from the upper part of the formation appear to have somewhat higher yields of clean coal at 10 per cent ash as compared to those in the middle and lower part of the formation.

A comparison of the washability characteristics using the clean-coal curve is quite difficult, as the yield-ash relationship is very much coal dependent, and suffers from many drawbacks. Above all, it is not a quantitive measure.

Near Gravity Material as a Measure of "Ease of Washing"

The amount of material in the range +/- 0.1 of density of separation is considered to be a more quantitive measure for comparing the "ease of washing". Difficulties of washing are categorized on the basis of the amount of near-gravity material at the density of separation for the desired clean-coal product (Leonard, 1979). The +/- 0.1 specific gravity range approach assumes that all material lying within this range contributes to difficulties in washing. However, this assumption, may not be accurate for washing in more efficient separators, operating within much narrower ranges (e.g., +/- 0.05 s.g.). Figure 5 depicts the amount of near-gravity material (+/- 0.1 s.g.) for seams from both studied coalfields.

The amount of near-gravity material close to the density of separation rates coal seams from Peace River as moderately difficult to very difficult to wash. The designation "moderately difficult" was assigned to the two highest clean-coal ranges and "very difficult" to the lowest range. The coal seams from East Kootenay coalfield are classified as "simple" for the highest

Table 2. Distribution of coal seams from Peace River and East Kootenay according to their yield of clean coal product at 10% ash reported with raw ash and top size ranges.

	PEACE RIVER COALFIELD			EAST KOOTENAY COALFIELD		
RANGE of YIELD at 10% ASH	NUMBER of SAMPLES	RAW COAL ASH RANGE	TOP SIZE mm	NUMBER of SAMPLES	RAW COAL ASH RANGE	TOP SIZE mm
100 - 90	8(24)	11.82-14.85	100(4) 75(3) 50(1)	6(35)	8.37-13.42	100(6)
90-70	9(24)	15.42-28.41	150(4) 100(4) 75(1)	18(35)	16.21-28.45	100(8) 50(10)
<70	7(24)	21.11-35.00	100(6) 75(1)	11(35)	23.57-35.00	100(6) 50(5)

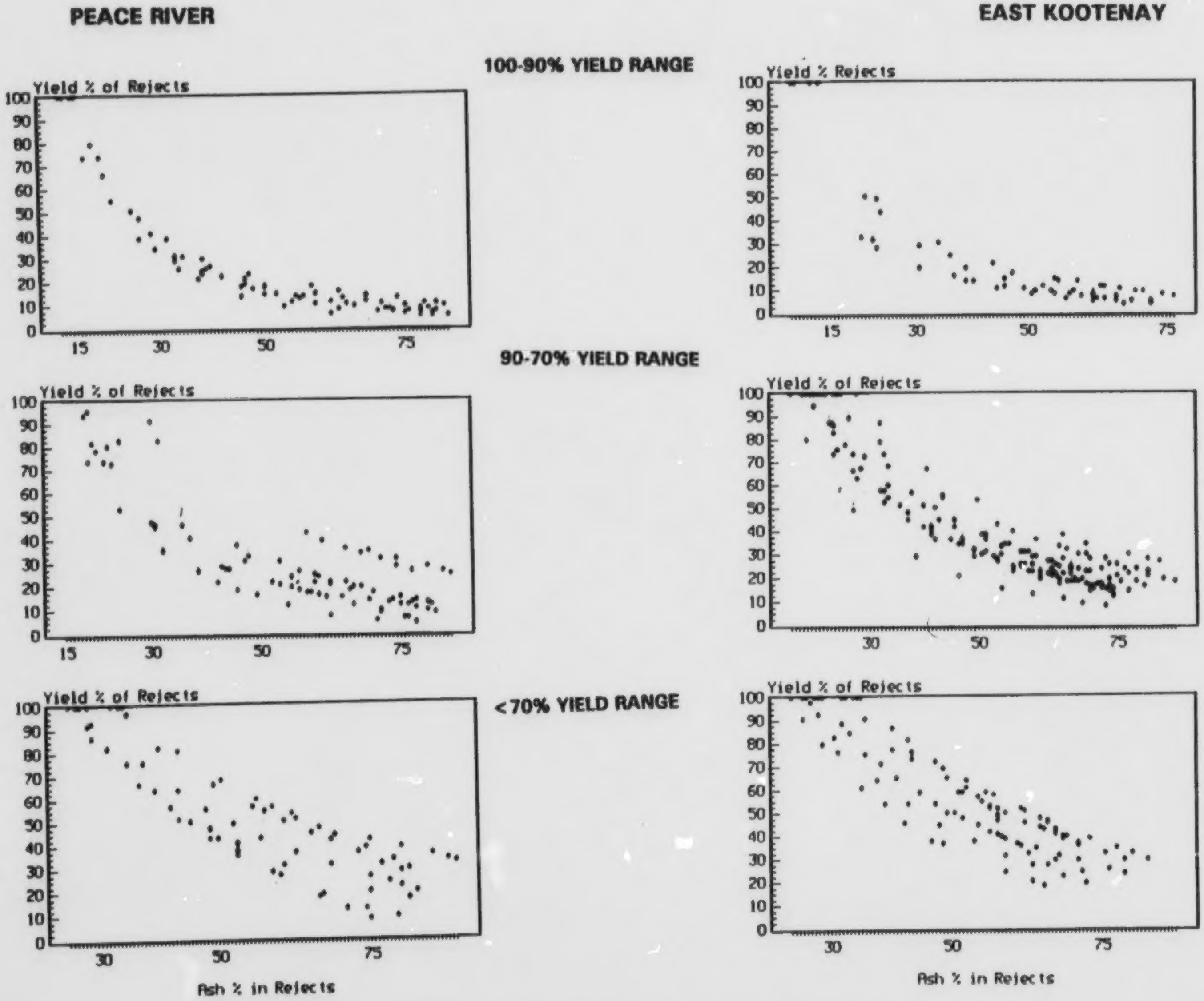

Figure 4. The ranges of variation for cumulative reject curves for seams falling within specified yield ranges from Peace River coalfield and East Kootenay coalfield.

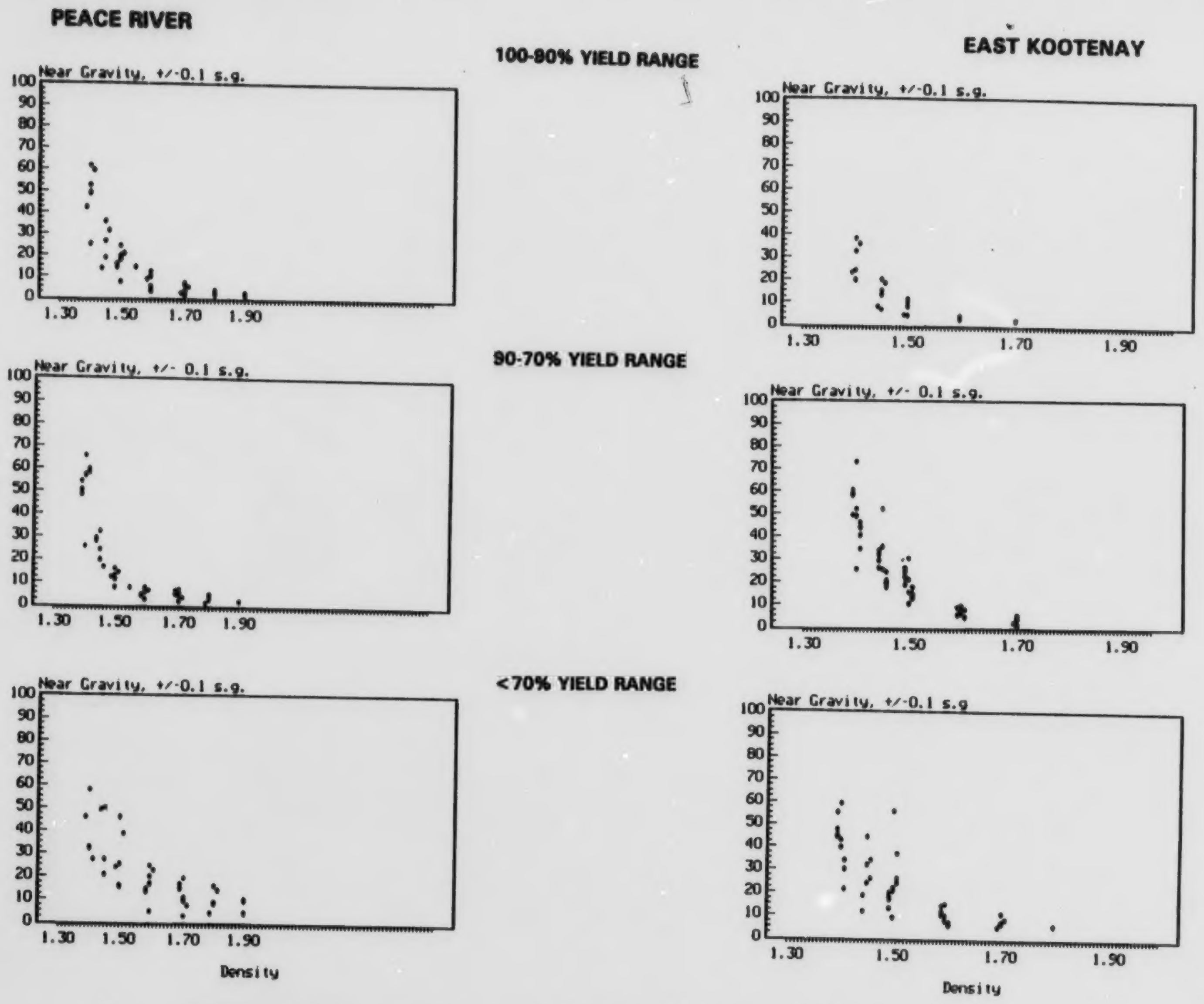

Figure 5. The range of variation for the amount of near-gravity material (+/- 0.1 s.g.) for specified yield of clean coal ranges in Peace River and East Kootenay coals.

yield range (Figure 5), moderately difficult for the second highest range and difficult for the coal seams in the lowest yield category.

Degree of Washing and Washability Number

Degree-of-washing plots were derived for the designated ranges of yield of clean coal for seams from the Peace River and East Kootenay coalfields (Figure 6). Very similar ranges of optimum degree of washing were found for the same yields of clean coal from both coalfields. Table 3 lists optimum degree of washing values, and washability numbers with the corresponding ash of clean coal and rejects, and the density at the optimum cut points.

The optimum cut point for the Peace River seams with highest yield of clean coal appears to be at a slightly higher density than for East Kootenay coal seams. The washability numbers associated with the various clean-coal yield ranges imply that Peace River coals are much more difficult to wash to the same clean-coal product levels than the East Kootenay coals. The average washability number for Peace River coals is 88 compared to 136 for East Kootenay coals. For the second range 64 compares with 71. For the third range the washability numbers are not significantly different.

The important conclusion to be drawn from the data in Table 3 is that even when the clean coal products at narrow yield ranges are compared within the same coalfield, the washability characteristics vary greatly. In other words, the difficulties in achieving the same coal product vary tremendously between different seams. This is evident from the wide range of washability numbers within designated yield ranges of clean coal.

The variation in washability numbers within the same geological formation varies from 39 to 185, with no consistency or relation to stratigraphic position. The washability number of two adjacent seams can be just as variable (72 to 142).

Liberation Patterns

The washability of any coal seam is very much dependent on the top-size of its representative sample. Liberation of coal from mineral matter is usually achieved by reducing the size of coal by breaking or crushing. During breakage coal particles separate from inclusive minerals, usually along the bedding planes. The way in which coal separates from ash-forming impurities, depends on the type and mode of occurrence of minerals as well as the type of coal. The easiest to separate are the epigenetic minerals, whereas epiclastic and syngenetic minerals are the more difficult to remove by physical methods (Cook, 1981; Falcon and Falcon, 1983; Holuszko and Grieve, 1990).

Table 3. Characteristics at optimum " degree of washing" for seams from the Peace River and East Kootenay coalfields.

RANGE of YIELD at 10% ASH	DEGREE of WASHING		ASH in CLEAN COAL at Nopt		ASH in REJECTS		DENSITY of SEPARATION	WASHABILITY NUMBER	
	MIN - MAX	*AVG*	MIN - MAX	*AVG*	MIN - MAX	*AVG*		MIN-MAX	*AVG*
PEACE RIVER COALFIELD									
100-90	40.4-56.7	*47.3*	3.5-6.2	*5*	16.5-46.7	*32.1*	1.42	48-163	*88*
90-70	40.8-51.9	*45.8*	5.7-8.5	*7.3*	25.6-73.91	*51.3*	1.48	54-90	*64*
<70	30.3-47.5	*37.5*	9.3-14.5	*11.5*	45.01-75.9	*56.8*	1.57	21-51	*33*
EAST KOOTENAY COALFIELD									
100-90	41.3-55.0	*49.9*	2.9-5.4	*4*	20.9-34.4	*24.7*	1.36	76-185	*136*
90-70	39.6-54.2	*48*	5.4-9.4	*7.1*	27.5-76.8	*52.6*	1.49	45-101	*71*
<70	29.6-44.3	*39.3*	8.6-13.8	*10.4*	38.8-68.1	*56.9*	1.55	22-51	*39*

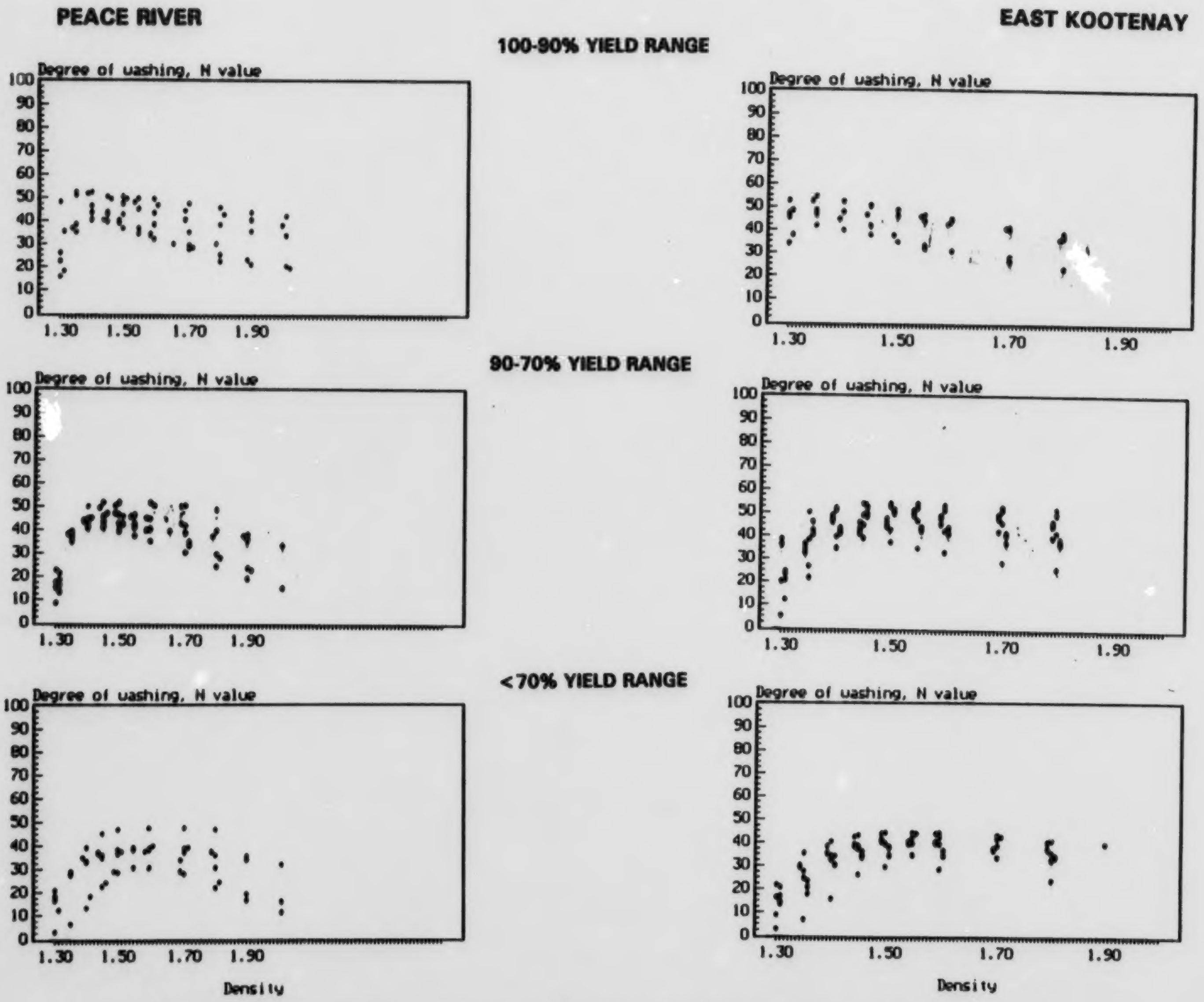

Figure 6. The range of variation for the degree of washing, for specified yield of clean coal ranges in Peace River and East Kootenay coals.

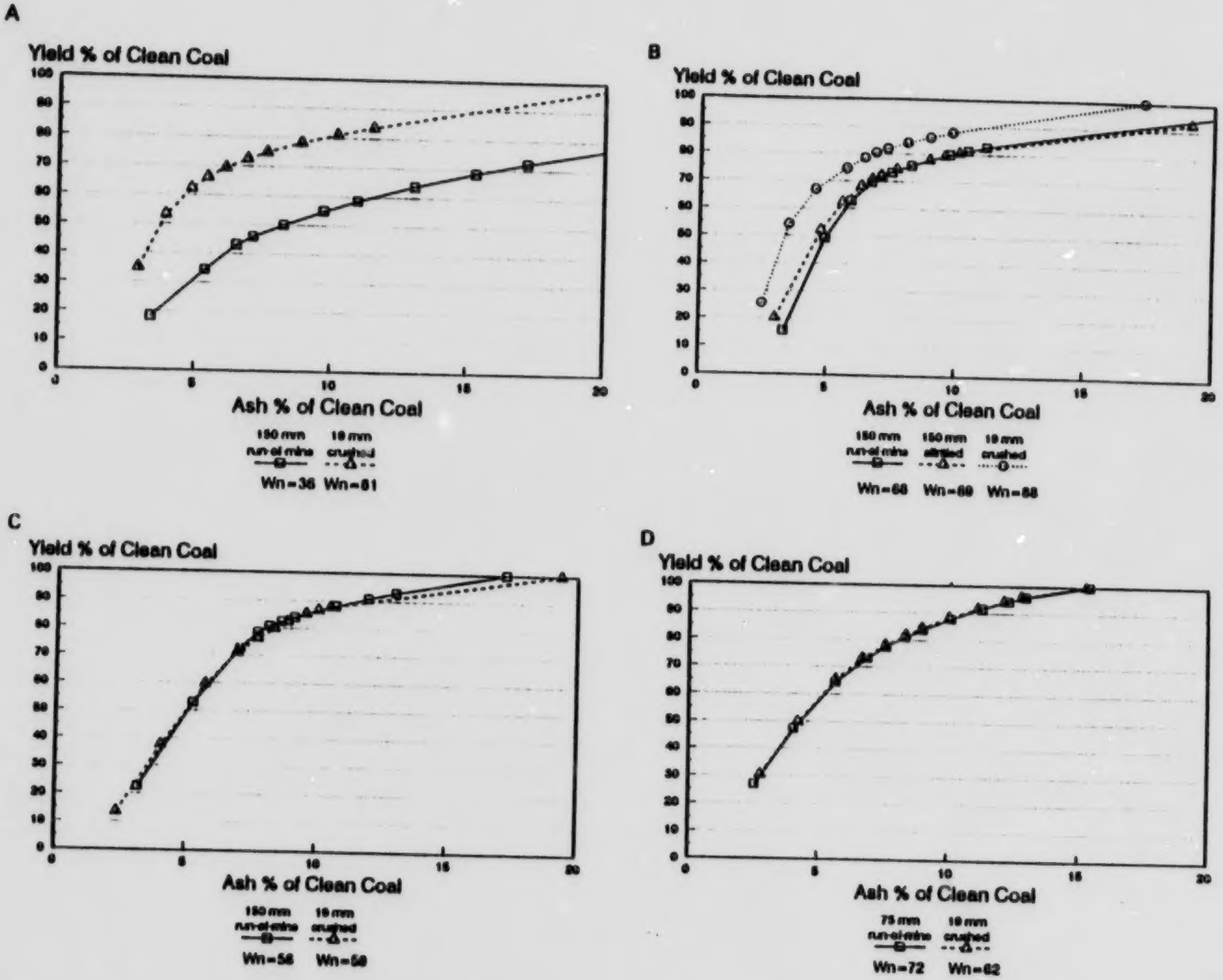

Figure 7. Liberation patterns for four coals from the Peace River coalfield.

For coals with epigenetic minerals concentrated along the cleats, reducing the size will lead to an easy physical separation of liberated minerals, and result in an increase in the yield of clean coal. For minerals of epiclastic origin (chiefly clays and quartz) liberation-separation may be difficult, as coarse crushing will not liberate the coal from associated minerals.

Figure 7 illustrates liberation patterns for four different coal seams from the Peace River coalfield. All four coals are from the Gates Formation. A reduction in the top-size of the run-of-mine sample resulted in: a substantial increase in the yield of clean coal (a); some increase in the yield of clean coal (b); almost no increase in the yield of clean coal (c); and no increase in the yield of clean coal (d). This is reflected in the increase of the washability number, for coals a, b, and c, and a slight decrease in value for the fourth coal.

Liberation characteristics of the four coals are quite different, indicating wide variations in the mode of occurrence of mineral matter in these seams. From the analysis of washability numbers, it is seen that only in the case of seams (a) and (b) can the ease of washing and recovery of clean coal be improved by size reduction. For seam (c) the reduction in size has almost no positive effect on the washability number. An interesting trend is observed in seam (d), where crushing to a smaller size leads to a decrease in ease of washing. However, there is no indication of a decrease in the yield of clean coal as seen in Figure 7 (d). This implies that the washability number detects changes in ease of washing better than the clean-coal curve does.

Systematic computation of washability numbers at various levels of crushing will aid in assessing the mode of association of mineral matter with coal, and the extent of liberation of mineral matter from coal.

SUMMARY AND CONCLUSIONS

This comparative study of washability of coal samples from two major British Columbia coalfields resulted in the following conclusions:

- washability characteristics of seams from both the Peace River and East Kootenay coalfields are variable to the same extent. Seventeen out of twenty-four samples from the Peace River coalfield yielded more than 70 per cent of clean coal product at 10 per cent ash, as compared to twenty-four out of thirty five from East Kootenay.

- the quality of rejects is highly variable for samples falling into the three different ranges of clean-coal yield at 10 per cent ash, in both coalfields.

- from the amount of near-gravity material (+/- 0.10 s.g.) at the density of separation required for good quality clean coal, the East Kootenay seams yielding the most clean-coal product were classified as simple to wash, whereas the seams from Peace River falling into the same category were found to be moderately difficult to wash.

- the "optimum degree of washing" and the ash content of clean coal were found to be very similar for seams from both coalfields, however, washability numbers obtained for different ranges of yield of clean coal were found to be much greater for the East Kootenay coalfield than for Peace River. This was especially true for the seams yielding the most clean coal (100-90% yield range), which were from the upper half of the Mist Mountain Formation. The higher washability numbers for the East Kootenay seams implies that these seams can be washed much more easily to the same clean coal product than their counterparts from Peace River;

- there is no significant trend or correlation between the washability number and stratigraphic position in the Gates Formation coals;

- the great variation in washability numbers within both coalfields indicates diversity in ease of washing among these seams;

- examples of different liberation patterns of coal during size reduction confirms significant variation in washing characteristics; the washability number is a better indicator of the liberation characteristics of coal than the clean coal curve derived from classical washability parameters.

ACKNOWLEDGMENTS

I wish to express my gratitude to the geology staff at all the province's coal mines for their cooperation, especially the staff of Greenhills and Line Creek mines for their assistance in this year's sampling program and supplying additional coal quality data. A special thanks is also due to David Grieve and Ward Kilby, who read an earlier version of this paper and contributed to its improvement.

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WASHABILITY OF BRITISH COLUMBIA COALS

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Washability of Peace River (northeast British Columbia) and East Kootenay (southeast British Columbia) coal seams are studied and compared. The washability characteristics of seams from both areas are quite variable.

The washability and their relative "ease of washing" is studied using parameters such as Degree of Washing and Washability Number. The degree of washing takes into account ash of raw coal, ash of clean coal and the yield of clean coal at the density of separation. Washability number is calculated as the ratio of the optimum degree of washing N_{opt}, to the ash of clean coal at this point. These numbers appear to be more suitable for comparisons than traditional yield-ash or yield-density relationships, since they pertain more to the coal intrinsic properties.

The scale of variation in washability characteristics among seams from both coalfields is very wide. The washability numbers for the Peace River coalfield vary from 21, for most difficult to wash, to 163, for easiest to wash seams. For East Kootenay the washability numbers vary from 22 to 136 respectively. The average washability number for the seams from Peace River is 63 and for East Kootenay 72.

NOTES

COAL PLANNING AND SURFACE GEOPHYSICS AT COAL MOUNTAIN

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Abstract

The coal deposit at Coal Mountain of southeastern British Columbia is extremely structurally complex. In situ coal is highly sheared along or near fault zones and fold axes and has numerous intercalations of siltstone and mudstone. Raw coal feedstock from these zones consist of finer sized coal, mixed coal and non-coal material which create washability problems resulting in reduced yield, higher product ash content and higher operating cost.

A surface geophysical program completed at Coal Mountain was successful in locating these zones within the Mammoth coal seam using electrical and electromagnetic methods. Independent verification of faults and parting material was completed through mapping and close spaced drilling.

The washability properties of the zones of sheared and mixed coal were compared to unsheared or less intercalated coal. Coals of similar raw ash contents showed reduced yield in the coal that was more highly sheared or intercalated. Target product ash specification for some of these coals was not achieved. Where coal types were blended to reduce the higher fines content and parting material, the yield improved and product specification was achieved.

It is concluded that detection of faults or parting material within coal is possible through surface geophysics. Where a program of blending coals is maintained, the results are higher yields, acceptable product quality and consequently lower production costs.

1.0 INTRODUCTION

The Coal Mountain Coal deposit is located in the CrowsNest coalfield of southeastern British Columbia (Figure 1). Coal produced at Byron Creek Collieries is a medium volatile bituminous coal suitable for both thermal and weak coking coal markets. Traditionally raw coal feedstock has been subdivided on the basis of raw ash content into 5 ash groups: very low ash (VLA) <16% ash, low ash (LA) 16 - 22% ash, medium ash (MA) 22 - 30% ash, high ash (HA) 30 - 40% ash and very high ash (VHA) 40 - 50% ash. Distribution of these ash groups was determined by a program of close spaced drilling. Coal planning had been focussed entirely upon the relationship of ash to specific gravity for planned washability characteristics and yield assumptions. Recent problems including lower than projected yields, inconsistent product quality and higher operating costs were recognized and attributed to anomalous characteristics of coals, such as higher content of finer sized coal and increased oxidation of coal and a higher degree of coal and non-coal mixing associated with fault zones and partings.

A project was proposed to determine if the fault zones and partings affected the coal washability and product quality. This project consisted of a detailed examination of close spaced drilling and mapping of faults and partings, a surface geophysical program to detect these anomalous zones and an evaluation of the washability characteristics of the different coals in the project coal zone.

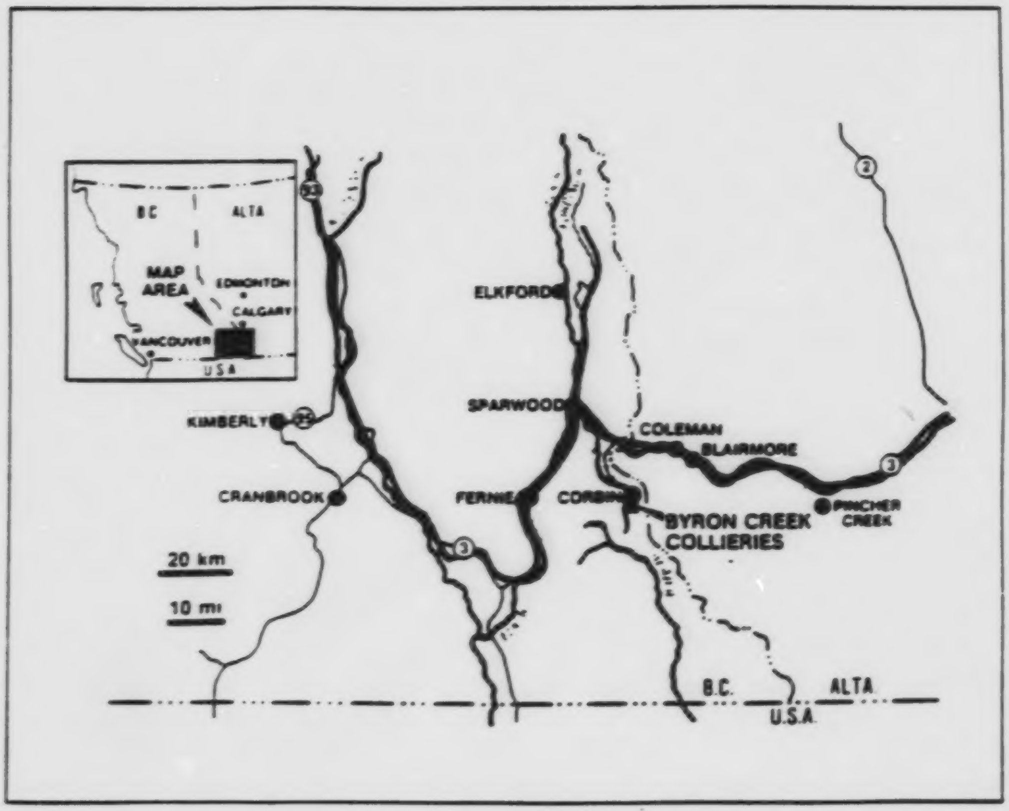
B.C
ALTA
MAP AREA
EDMONTON
CALGARY
VANCOUVER
U.S.A
93
ELKFORD
KIMBERLY
95
CRANBROOK
SPARWOOD
COLEMAN
BLAIRMORE
FERNIE
CORBIN
BYRON CREEK COLLIERIES
PINCHER CREEK
3
20 km
10 mi
B.C.
ALTA.
U.S.A.

Figure 1. Location of Byron Creek Collieries - Coal Mountain.

2.0 COAL GEOLOGY

Coal at Coal Mountain is found primarily in the Mammoth or No.1 Seam of the Mist Mountain Formation and is estimated to be 30 meters in thickness (Figure 2). Numerous lenses and intercalations of claystone and siltstone are known to occur within the seam as a result of the depositional environment.

The coal bearing unit is underlain by the Moose Mountain sandstone, a competent, medium to coarse sandstone member of the Morrisey Formation. The Mist Mountain Formation clastic sequence, consisting of interbedded sandstone, siltstone and mudstone, overlies the Mammoth coal seam. The Mist Mountain Formation, including the coal sequence, is less competent than the Moose Mountain member and upon tectonic deformation has been severely distorted.

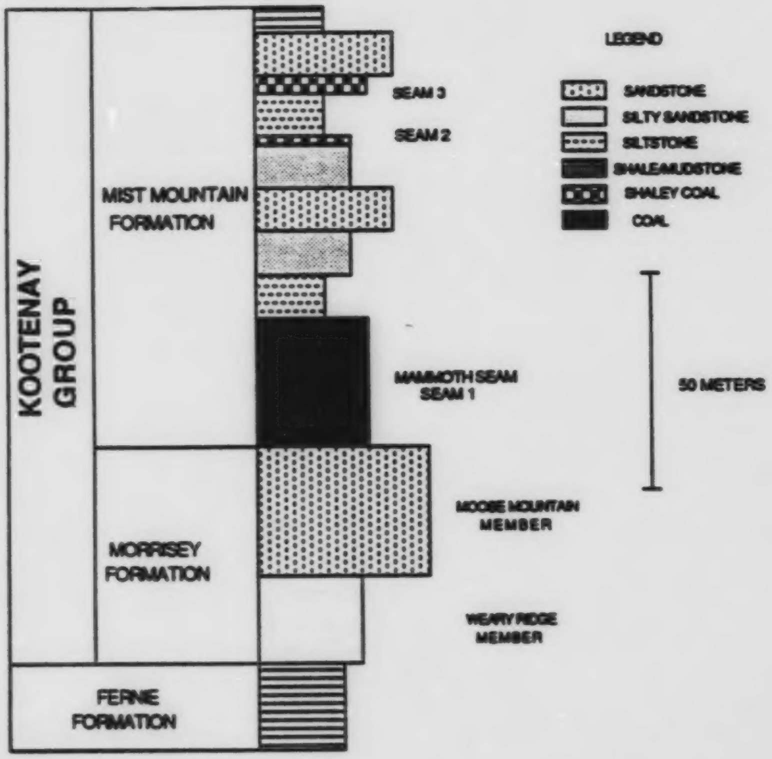
KOOTENAY GROUP
MIST MOUNTAIN FORMATION
MORRISEY FORMATION
FERNIE FORMATION
SEAM 3
SEAM 2
MAMMOTH SEAM
SEAM 1
MOOSE MOUNTAIN MEMBER
WEARY RIDGE MEMBER
LEGEND
SANDSTONE
SILTY SANDSTONE
SILTSTONE
SHALE/MUDSTONE
SHALEY COAL
COAL
50 METERS

Figure 2. Stratigraphy of Coal Mountain.

The intense structural deformation, including multiphase faulting and folding, has created areas where coal reaches thicknesses in the order of 100 meters (Figures 3 and 4). Numerous and more closely spaced fault zones within the coal exhibit crenulation, slickensides and finer sized, flakey coal.

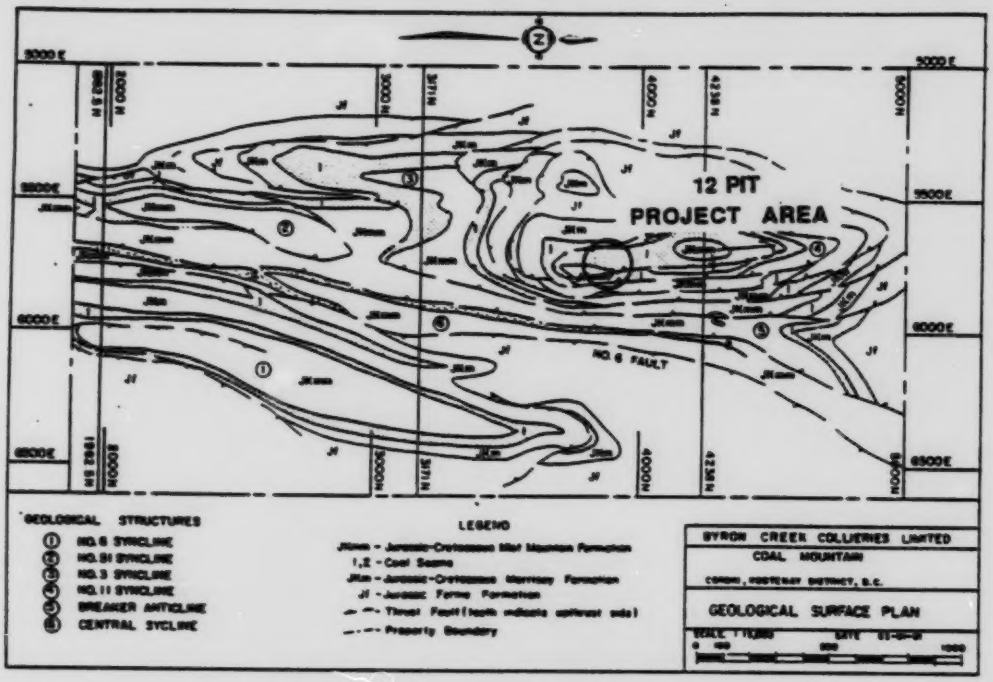
12 PIT
PROJECT AREA
NO. 6 FAULT
5000E
5500E
6000E
6500E
1962.5N
2000N
3000N
3171N
4000N
4238N
5000N
JKmm
JKm
Jf
GEOLOGICAL STRUCTURES
① NO. 6 SYNCLINE
② NO. 31 SYNCLINE
③ NO. 3 SYNCLINE
④ NO. 11 SYNCLINE
⑤ BREAKER ANTICLINE
⑥ CENTRAL SYCLINE
LEGEND
JKmm - Jurassic-Cretaceous Mist Mountain Formation
1,2 - Coal Seams
JKm - Jurassic-Cretaceous Morrissey Formation
Jf - Jurassic Fernie Formation
Thrust Fault (teeth indicate upthrust side)
Property Boundary
BYRON CREEK COLLIERIES LIMITED
COAL MOUNTAIN
CORBIN, KOOTENAY DISTRICT, B.C.
GEOLOGICAL SURFACE PLAN
SCALE 1:10,000
DATE
0
500
1000

Figure 3. Structural Map of Coal Mountain.

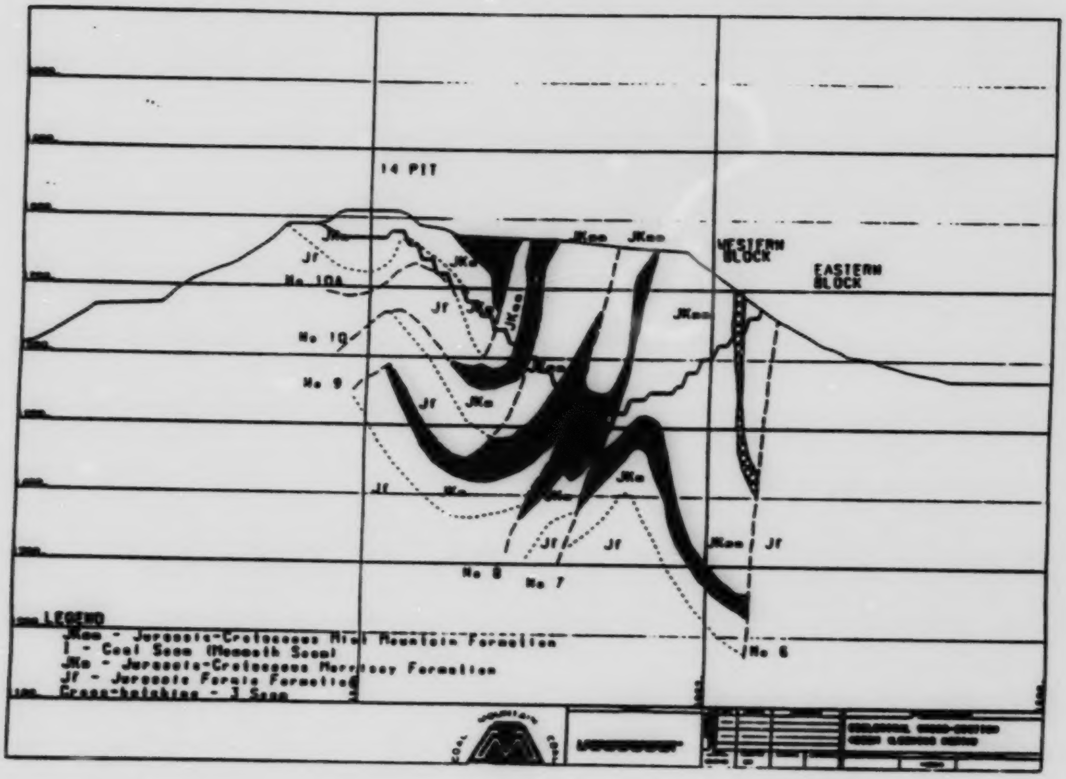
14 PIT
JKmm
Jf
No. 10A
No. 10
No. 9
JKm
WESTERN BLOCK
EASTERN BLOCK
No. 8
No. 7
No. 6
LEGEND
JKmm - Jurassic-Cretaceous Mist Mountain Formation
1 - Coal Seam (Mammoth Seam)
JKm - Jurassic-Cretaceous Morrissey Formation
Jf - Jurassic Fernie Formation
Cross-hatching - 1 Seam
COAL MOUNTAIN

Figure 4. Typical Cross-section of Coal Mountain.

3.0 COAL PREPARATION AT BYRON CREEK

The coal preparation facilities at Byron Creek Collieries consist of a Baum Jig Plant for processing coarse VLA and LA coals, and a Heavy Media Plant for processing higher ash coals and a blend of fine and coarse coals (Figure 5). The heavy media plant consists of heavy media cyclones which clean raw coarse (+28 mesh size) feedstock and two stage water only cyclones for cleaning the finer (28 X 100 mesh size) material. The facility has no froth flotation circuit so the 100 X 0 mesh size coal is not cleaned and reports directly to the filters. From there it is either rejected or included in the final product depending upon the ash content of the overall product stream.

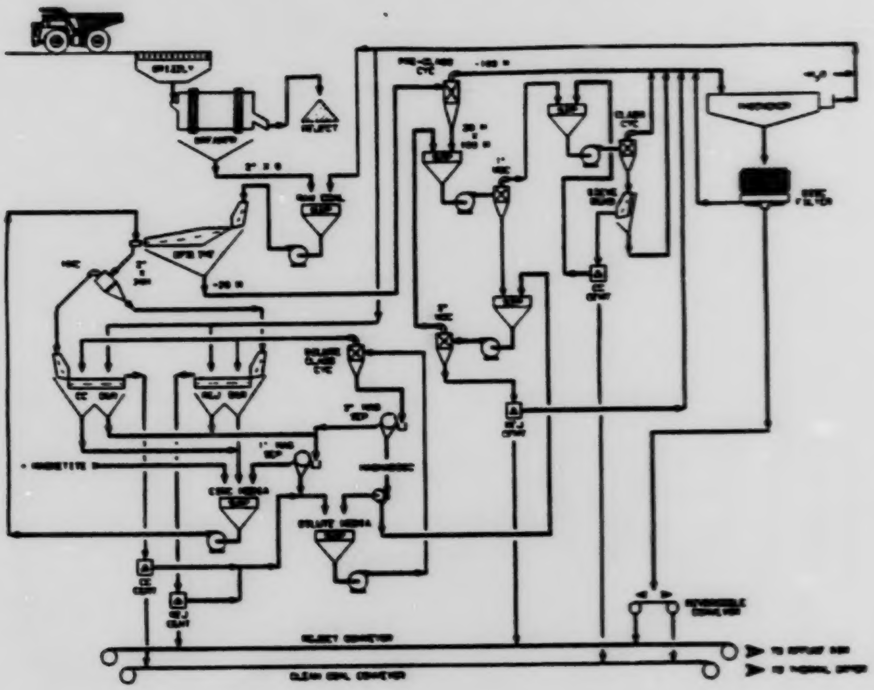
REJECT
PRE-CLASS CYC
-100 M
CLASS CYC
-28 M
DISC FILTER
MAGNETITE
CONC MEDIA
DILUTE MEDIA
REVERSIBLE CONVEYOR
REJECT CONVEYOR
CLEAN COAL CONVEYOR

Figure 5. Diagram - Byron Creek Collieries Coal Preparation Plant.

The typical planned size distribution of feedstock for the preparation plant was expected to be 70% of +28 mesh size material and 30% of -28 mesh size material. However in highly sheared and faulted zones there can a noticeable increase in the finer portion up to 40+% of -28 mesh size material. This increased fraction of fines overloads the water only cyclones and disc filters creating slow downs in throughput, higher ash to product or increased reject material, inefficiencies on the heavy media cyclones and subsequently lower yields.

4.0 SURFACE GEOPHYSICAL METHODS FOR FAULT AND PARTING DETECTION

The detection of faults and other geological phenomena in coal using geophysical methods such as electrical (DC profiling) and electromagnetic methods (EM31 and Max-Min) in this type of application was not previously known. As coal is generally a very resistive material it was postulated that differences in the resistivity across a zone could be measured and attributed to fault planes or parting material that would act as conductors due to clay content or alteration within the zones. Therefore methods focussing on measuring resistivity or conductivity or relative changes in these features in the subsurface would be utilized. A brief description of each method is reviewed below.

4.1 Direct Current (DC) Resistivity Profiling

Direct Current (DC) Resistivity Profiling involves driving electrical current into the ground through a pair of current electrodes. The current distribution in the earth is mapped by measuring the voltage across a second pair of electrodes and mapping the changes in resistivity. A semi-log profile plot of the apparent resistivities is produced and interpreted.

4.2 Electromagnetic Induction Methods

Electromagnetic Induction Methods involve inducing a current flow in the ground using a time varying magnetic dipole source. The current flow induces a secondary magnetic field which is sensed by a receiver dipole. The measured amplitude and phase of the secondary field is related to the distribution of resistivity in the subsurface. Max Min I Horizontal Loop and EM31 Ground Conductivity are two methods used in this project.

With Max Min I the depth of penetration can be varied by altering the transmitter-receiver coil geometry, or the frequency. For EM31 the transmitter is rigidly mounted fixing the coil separation at 3.66 meters with alteration in the depth of penetration only through changing coil separation or operating height. Profile plots of the conductivity for each method are created and subsequent interpretation of the distribution of resistivity completed.

5.0 PROJECT OBJECTIVES

The project objectives were:

1) to determine if fault zones and parting material can be detected in the field using integrated geophysical and geological interpretative techniques.

2) to determine if a relationship exists between inferior coal washability characteristics and coals from fault zones and intermixed parting material by identifying these zones and assessing washability characteristics for these coals against unaltered zones.

3) to demonstrate that a proper program of coal planning and blending using knowledge of inferior washing coals through geophysics and geology is a cost effective way to aid coal beneficiation, improve coal product quality and lower overall operating costs.

The project would be conducted on a designated area in 12-PIT on the 1770 bench located at 5750E and 3800N (Figure 3). A geological interpretation using close spaced drilling information and mapping during production would be completed. A series of 10 lines of geophysics would be completed across the zone with 8 lines perpendicular to the geological strike, 1 parallel to the geological strike and 1 at 45 degrees to the geological strike. The interpreted geophysical data would then be compared to the geological interpretation after the coal was mined.

An assessment of the coal washability from the various sheared and unsheared zones would then be compared to the coal characteristics as interpreted from the geology and geophysics to see if a correlation existed.

6.0 PROJECT RESULTS

6.1 Geophysical Methods - Electromagnetics

Max Min I electromagnetic methods were used to cover the 10 lines (A through J) with the transmitter and receiver loops in horizontal coplanar configuration. Three frequencies, including 1760 hz, 7040 hz and 14080 hz, were used. The transmitter-receiver coil separation was constant at 25 meters. Line C was repeated using a station interval and a transmitter-receiver coil separation of 12.5 meters. Line E was repeated using a station interval of 12.5 meters and a transmitter-receiver coil separation of 25 meters. In general the strongest electromagnetic response occurred in the low frequency (1760 hz) survey. A compiled plot of the profiles with interpreted conductors for the 1760 hz data is shown in Figure 6.

EM31 conductivity surveys were completed at 5 meter intervals along lines A, B, C, D, G and J. Three different measurements, including VG - vertical coplanar coil mode at ground level, HZ - horizontal coplanar coil mode at hip level and HG - horizontal coplanar coil mode at ground level were completed. In general the EM31 data indicated very low conductivities over the survey grid. Two areas of high apparent conductivities were identified as conductors A and B on Figure 7. These anomalies correspond to a major fault zone with a rock parting (A) and a highly sheared fault zone in coal (B). A number of weaker conductors of limited strike also exist and may be related to the faulting.

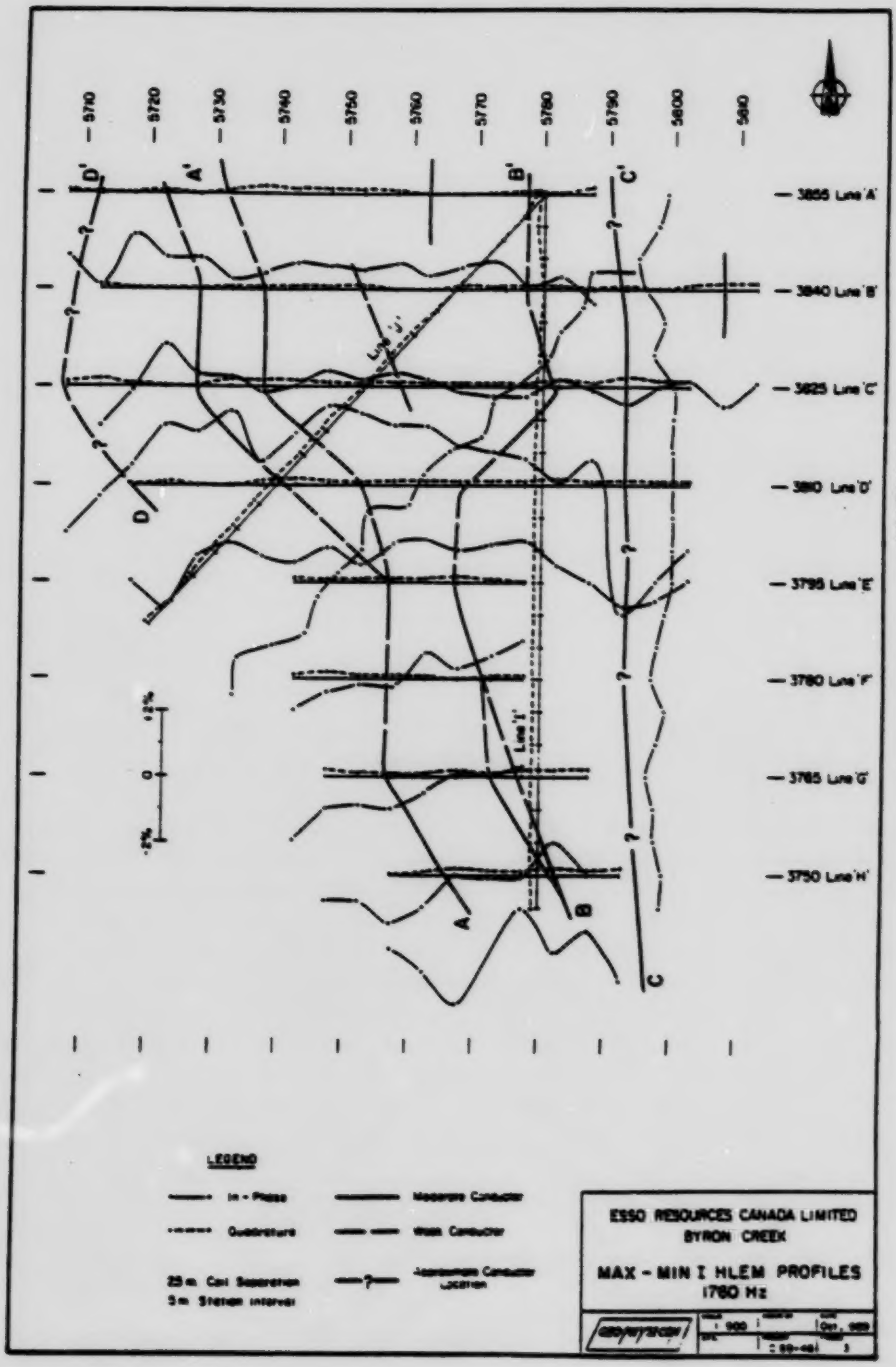
5710
5720
5730
5740
5750
5760
5770
5780
5790
5800
5810
3855 Line 'A'
3840 Line 'B'
3825 Line 'C'
3810 Line 'D'
3795 Line 'E'
3780 Line 'F'
3765 Line 'G'
3750 Line 'H'
D'
A'
B'
C'
D
A
B
C
Line 'J'
Line 'I'
+12%
0
-12%
LEGEND
In - Phase
Quadrature
25m. Coil Separation
5m. Station interval
Moderate Conductor
Weak Conductor
Approximate Conductor Location
ESSO RESOURCES CANADA LIMITED
BYRON CREEK
MAX - MIN I HLEM PROFILES
1780 Hz
1 : 500

Figure 6. Compiled plot of Max Min I survey data.

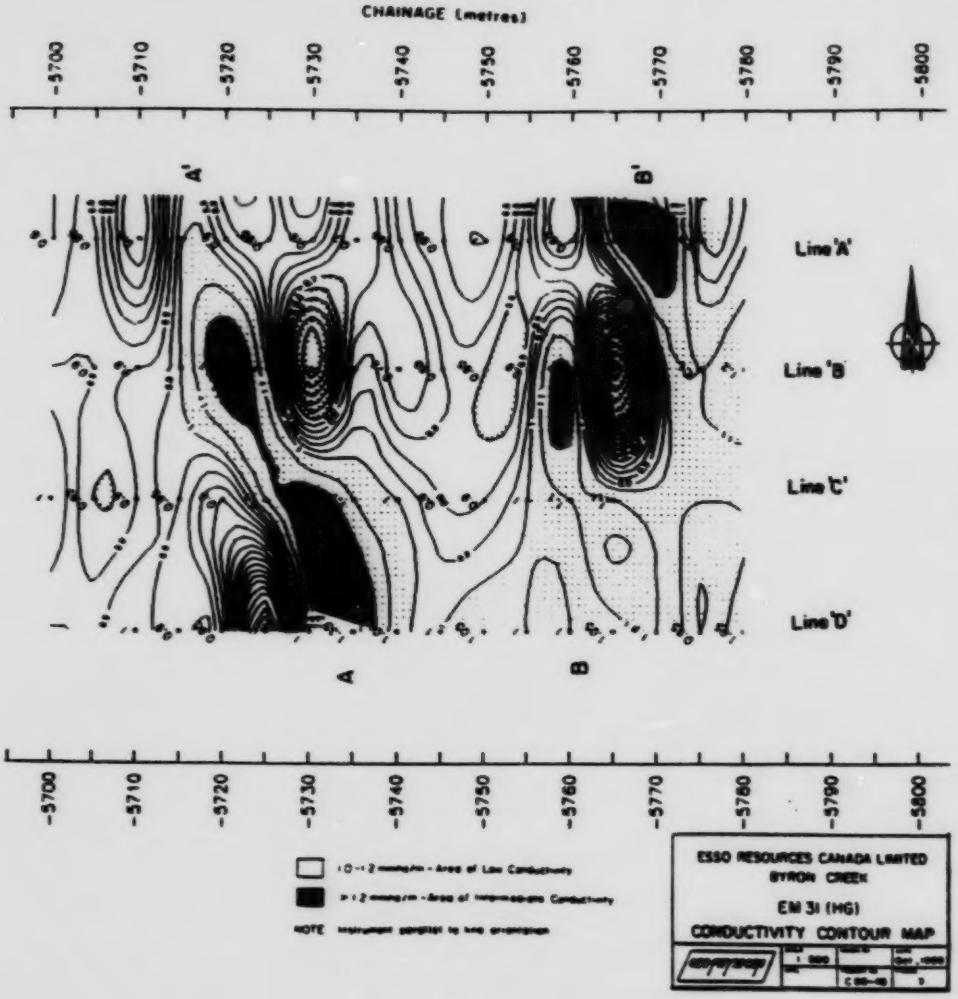
CHAINAGE (metres)
-5700
-5710
-5720
-5730
-5740
-5750
-5760
-5770
-5780
-5790
-5800
A'
B'
Line 'A'
Line 'B'
Line 'C'
Line 'D'
A
B
Area of Low Conductivity
Area of Intermediate Conductivity
NOTE
ESSO RESOURCES CANADA LIMITED
BYRON CREEK
EM 31 (HG)
CONDUCTIVITY CONTOUR MAP

Figure 7. Typical plot of EM31 data showing conductors.

6.2 Geophysical Methods - Electrical

Due to the cost and rapid advance of the mining operations only Line C was completed using the DC Resistivity Profiling method. Recorded voltage values were summed and the results averaged over the number of instrument iterations resulting in a smoothed data set for deriving apparent resistivity values. Four distinct zones of low apparent resistivity occur and are plotted as A, B, C and D on Figure 8. The magnitude of conductors A and B are similar for each electrode spacing and indicate continuity at depth. Conductors C and D are more prominent in the near electrode response indicating a more shallow depth of continuity. All conductors show a lateral shift along the surveyed line relative to increased electrode spacing, suggesting a westerly dip for the conductors.

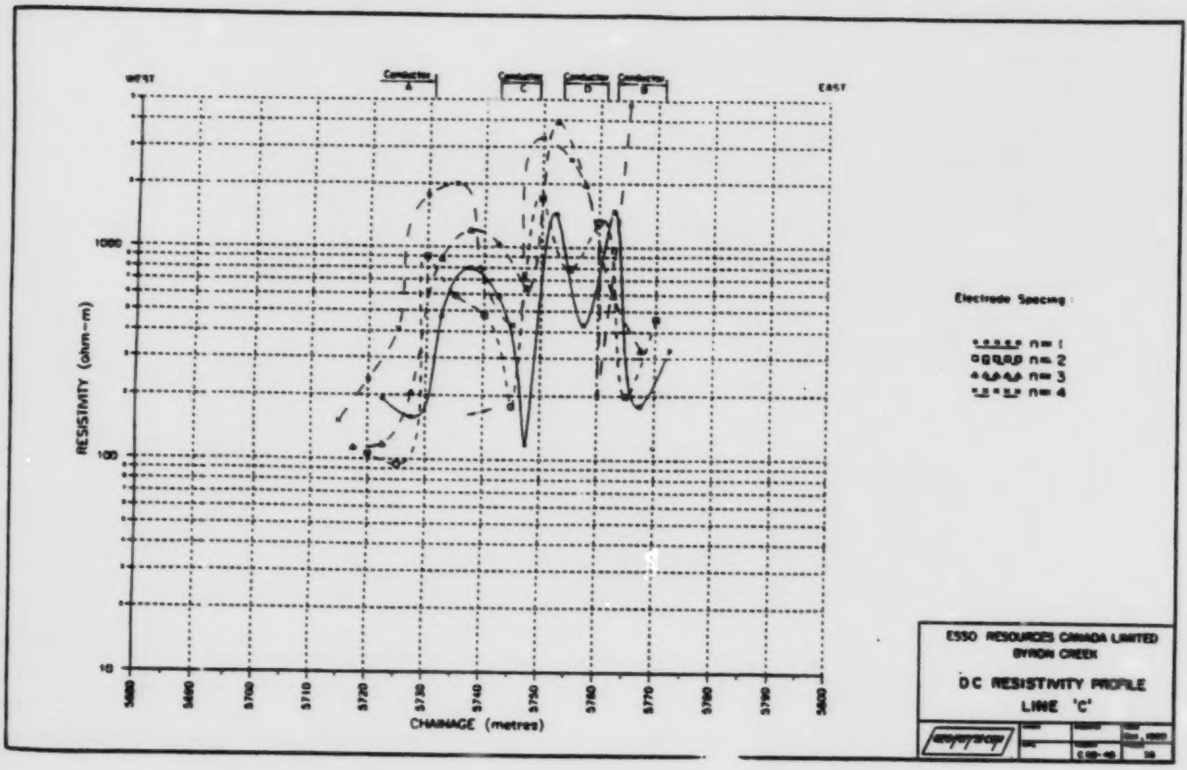

Figure 8. DC Resistivity Profile of Line C showing conductors.

6.3 Geological Interpretation

The surveyed area was previously drilled at a close spacing grid of 10 meters east-west and 15 meters north-south with drillhole depth of 30 meters and sample interval of 10 meters. Ash values derived from the proximate analyses of the drillhole samples were compiled and ash zonations designated. During the mining operation mapping of the fault zones and parting material was completed and a bench geology interpretation compiled using the close spaced drilling information and the mapping data (Figure 9).

6.4 Geological and Geophysical Correlations

Figure 10 represents a merged compilation of locations of faults and partings as interpreted geologically and those conductors interpreted as possible faults or partings from Max Min I and the DC Resistivity Profiling surveys. A strong correlation exists between the two interpretations indicating that subsurface detection of faults is possible and may be mapped over a considerable distance.

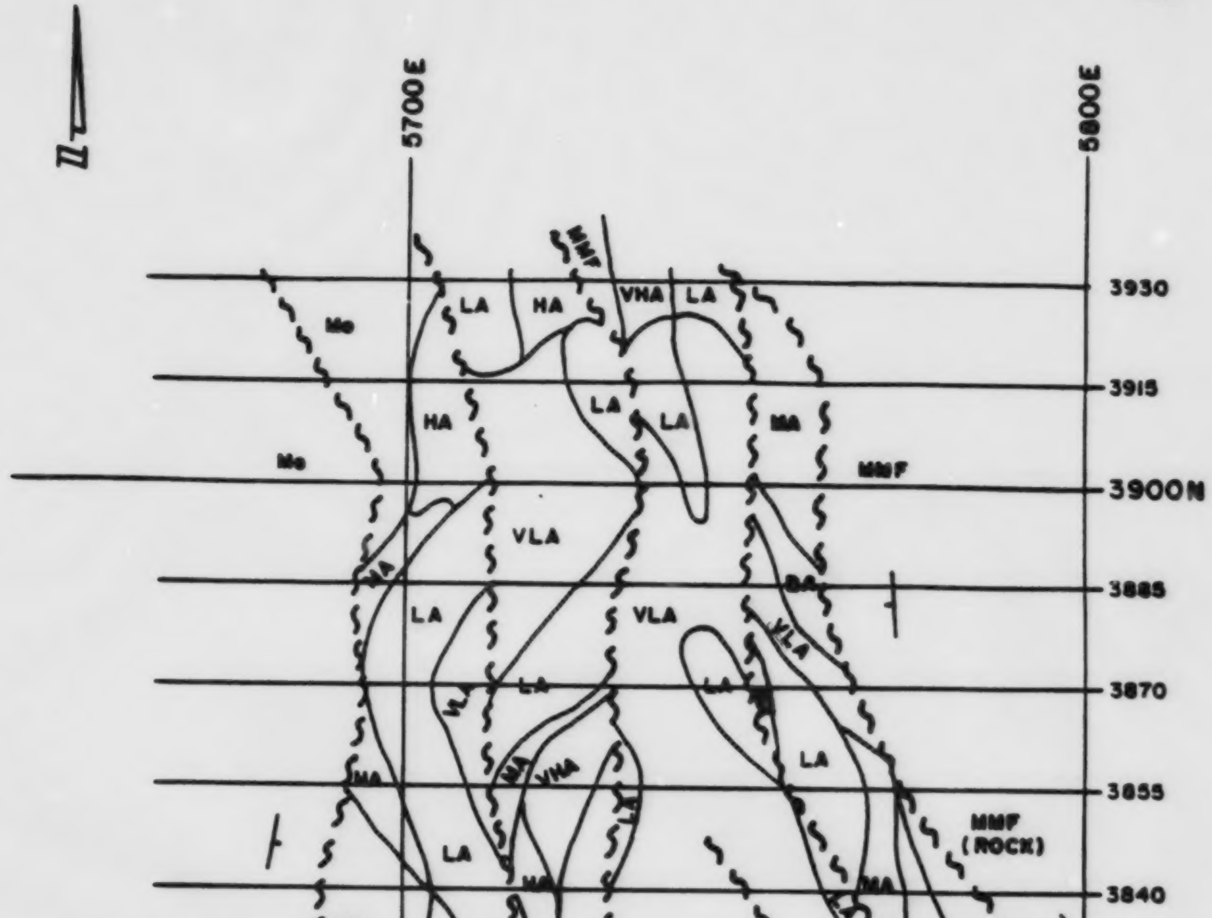
N
5700E
5800E
3930
3915
3900N
3885
3870
3855
3840
3825
3810
3800N
3795
3780
MMF
Mo
LA
HA
VHA
MA
VLA
BA
MMF (ROCK)
Mo (ROCK)
BYRON CREEK COLLIERIES
PIT 12 — 1770 BENCH
GEOLOGY AT 1775m ELEV.
Scale · 1:1000

Figure 9. Geological interpretation of project area.

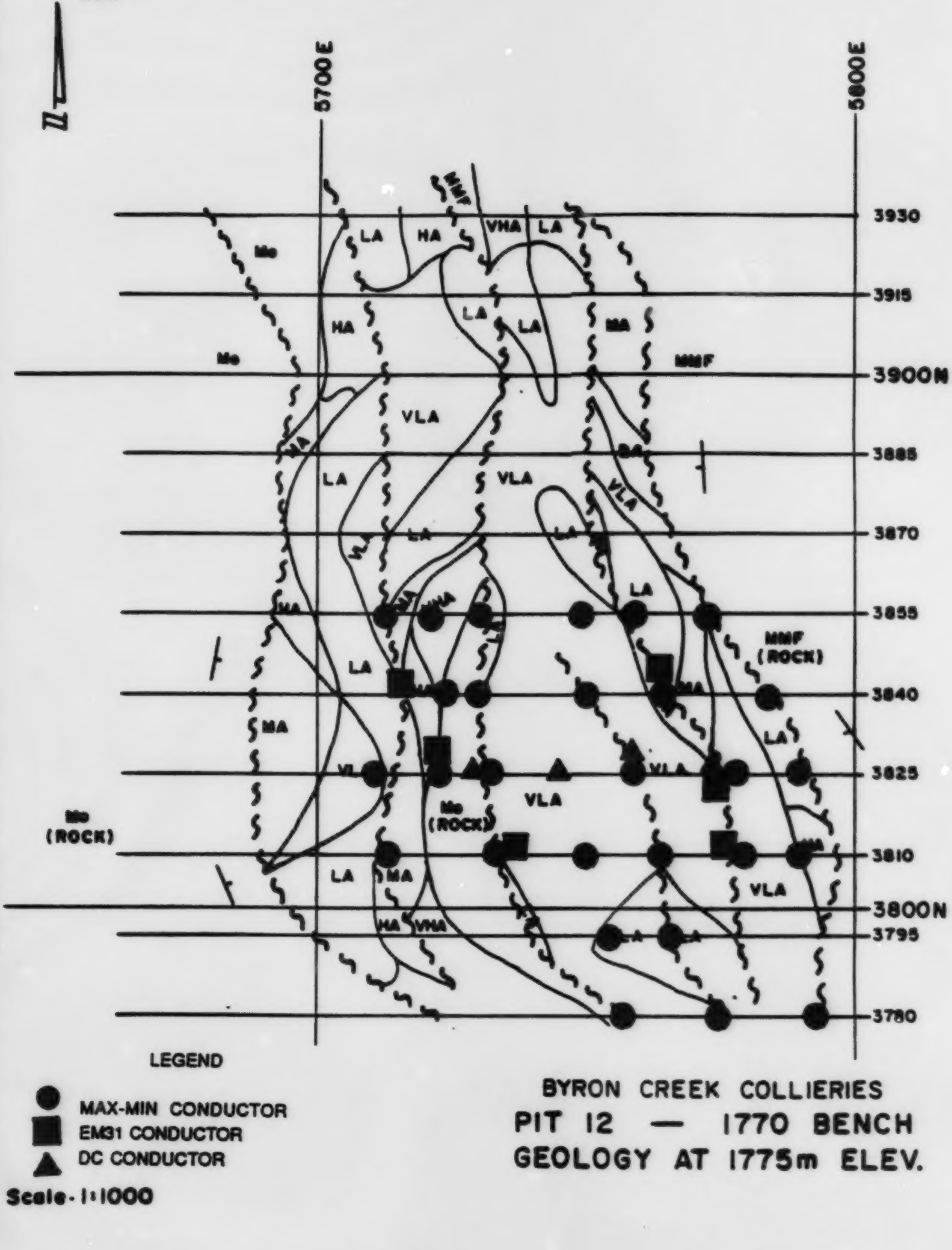
N
5700E
5800E
3930
3915
3900N
3885
3870
3855
3840
3825
3810
3800N
3795
3780
MMF
LA
HA
VHA
Me
MA
VLA
Me (ROCK)
MMF (ROCK)
LEGEND
MAX-MIN CONDUCTOR
EM31 CONDUCTOR
DC CONDUCTOR
Scale- 1:1000
BYRON CREEK COLLIERIES
PIT 12 — 1770 BENCH
GEOLOGY AT 1775m ELEV.

Figure 10. Correlation of faults using geology and geophysics.

6.5 Coal Beneficiation Results

Coal was mined from the surveyed area during the month of October for a weak coking product of 11.5% ash. Raw coal of the LA group (16 to 22% raw ash) is generally used for this feedstock. A cross plot of the raw coal feedstock and yield is shown for each shift of coal production (Figure 11). The areas that were mined from zones with influence of less than two faults as interpreted from the geology and geophysics are plotted as boxes. The coals that were mined with influence of two or more faults and achieved the target ash specification are plotted as solid dots. The coals that were mined with influence of two or more faults but did not achieve the target ash specification are plotted as shaded dots.

As can be seen a distinct correlation exists between the yield and the coals showing influence of the different fault categories. In general higher yields are associated with the less faulted and mixed zones. In addition coals that did not achieve the target product ash specification are generally those with influence of two or more faults. The overall range in yield for the production run was 52.5% to 76.5% for a real yield difference of 24%. The yield range for coal with two or more faults was 52.5% to 63.5% with a mean yield of 58%. The yield range for coal with less than two faults was 62.5% to 76.5% with a mean yield of 69.5%. The overall mean yield was 64%.

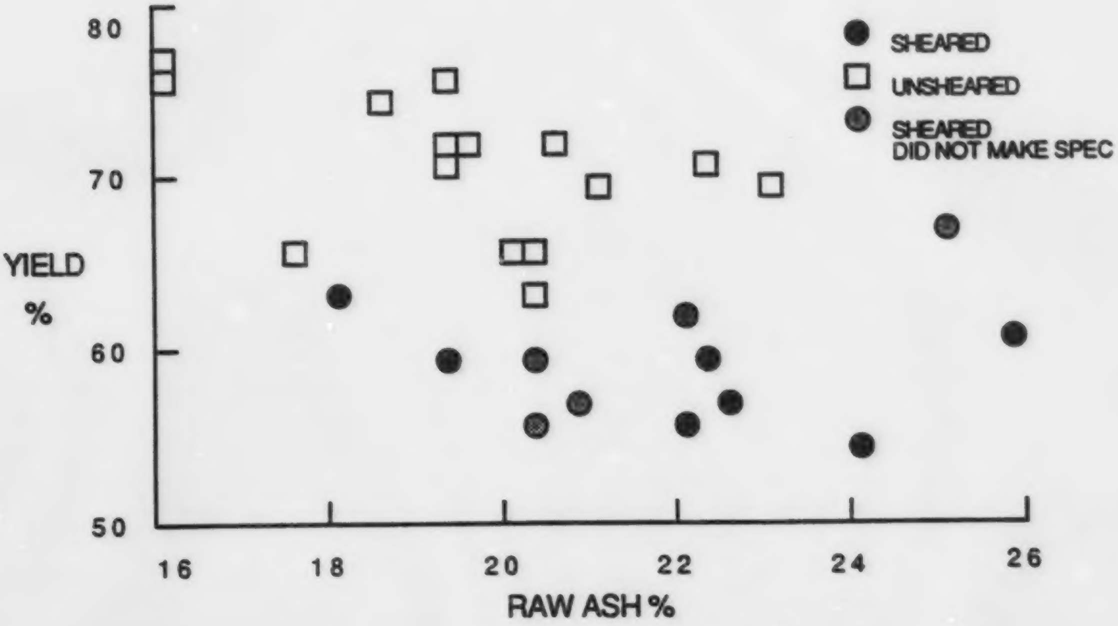

Figure 11. Yield vs. raw ash for sheared and unsheared coals.

7.0 DISCUSSION

7.1 Impact of Yield Differential on Operations

The impact on operations of the differential in yield can be demonstrated by using a hypothetical case for the mining and plant operation. The hypothetical case as shown in Table 1 shows the impact of yield over a ten shift production week to produce 22,520 tonnes of weak coking coal at 64% planned yield.

Raw feedstock of 35 200 tonnes of coal would be fed at a rate of 440 tonnes per hour to the coal preparation plant to produce a target of 22 520 tonnes per week at the planned yield. The mean yield for sheared coal is 58% thereby producing 20 420 tonnes of clean coal per week. This would necessitate mining an additional 3620 raw tonnes of coal to meet the target production at this yield. The unsheared coal at 69.5% yield recovers 4044 more tonnes of clean coal per week than sheared coal and would reduce raw coal feedstock to 32 402 tonnes. Blending the two coal types would achieve plan at 22,440 tonnes per week at a 64% yield.

Using an assumed cost of $25.00 per tonne of clean coal at 64% yield, a cost of $27.57 per tonne is realized at 58% yield using the sheared coal. Using unsheared coal at 69.5% yield reduces cost per tonne of clean coal to $23.01.

It can been seen that either cost savings per tonne or better coal reserve utilization can result. For this hypothetical case the difference between the sheared versus blended coal is 2100 tonnes of clean coal at $27.57 per tonne or about $58,000.00 in additional cost to achieve the target production. For the unsheared versus blended coal the cost saving is $1.99 per clean tonne and a cost saving of about $44,000.00. In addition for unsheared coals, the cost of rehandling for blending, estimated at $0.75 to $1.00 per tonne, would be saved.

	SHEARED COAL	UNSHEARED COAL	BLENDED COAL
RAW COAL/SHIFT	3520 TONNES	3520 TONNES	3520 TONNES
CLEAN COAL/SHIFT	2042 TONNES	2446 TONNES	2252 TONNES
RAW COAL/WEEK	35200 TONNES	35200 TONNES	35200 TONNES
CLEAN COAL/WEEK	20420 TONNES	24460 TONNES	22520 TONNES
YIELD %	58.0%	69.5%	64.0%
COST/CLEAN TONNE	$27.57	$23.01	$25.00

Table 1. Hypothetical case of coal production and costs for sheared, unsheared and blended coals.

7.2 Cost of Surface Geophysics vs. Cost of Coal Production

The typical costs for a program of surface geophysics to identify faults and partings within an operating coal mine can be variable depending on the method used. EM31 and Max Min I can cover approximately 2 kilometers of survey per day , whereas DC Resistivity Profiling can cover about 0.5 kilometers per day at three times the cost factor as electromagnetic methods. A cost estimate for the project area was $15,000.00 using electrical and electromagnetic methods and $5,000.00 for electromagnetic only.

It can be seen that the cost of production has a cost saving of $44,000.00 or an increase of $58,000.00 in costs will be incurred to meet the production target if the coal is unsheared or sheared coal. An expenditure of $5000.00 to $15,000.00 for geophysics over this project area would have allowed better planning for production, altered the mining sequence and ultimately lowered costs for production from this area.

8.0 CONCLUSIONS

From the project it can be concluded that:

1. Faults and partings are able to be detected using electrical and electromagnetic geophysical methods and correlated with geological phenomena.

2. At Byron Creek which does not have a fine coal cleaning circuit, the product quality and recovery of similar raw coals from different zones is affected by varying degrees of shearing or parting material.

3. The impact of coal recovery and operating cost through variations in coal quality and yield can be substantial. If identified using an integrated program of geology and geophysics and managed through a proper blending strategy during the coal planning and mining stages, coal reserve utilization and overall cost savings should be realized.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Grant Goddard, General Manager of Byron Creek Collieries, for his review of the paper and Byron Creek Collieries for their support of innovative applications in the field of coal mining and geophysics.

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Henderson, J. & Bowman, M. (1989): Integrated Geophysical Test Surveys to Determine Fault Zones within Coal at Byron Creek Collieries, British Columbia.

NOTES

UTILIZATION OF WESTERN CANADIAN METALLURGICAL COALS

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The paper will give a brief overview of international markets for metallurgical coal with specific reference to the role of Western Canadian coal. Technical attributes of Canadian coal and its performance in conjunction with other internationally traded coals will be discussed. The impact of new iron making technologies on Western Canadian coal exports will also be examined.

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Full paper is in proceedings volume after author index
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NOTES

USING GEOPHYSICAL LOGS TO PREDICT GEOTECHNICAL PARAMETERS IN SURFACE MINES

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ABSTRACT

The paper incorporates part of the results of a four year study conducted to establish correlations between downhole geophysical logs and geotechnical parameters for overburden formations in western Canadian surface mines. One study objective was to identify and refine methods that would increase the quantity of geotechnical data while maintaining quality and reducing collection costs. Databases consisted of geotechnical classification and strength test results and geophysical logs from an operating coal mine and a proposed coal mine site. The suite of logs included density, multi-channel sonic, short-spaced neutron, focussed electric resistivity, natural gamma and caliper logs. The study utilized data from approximately 50 drillholes selected from an overall database of some 400 holes. All holes were logged uncased with water as the drillhole fluid. In preparation for correlation analyses, the geotechnical data were edited to remove data gaps and the recorded core sample depths adjusted where necessary to ensure alignment with the digitized geophysical logs. Good correlations obtained include uniaxial compressive strength vs. sonic log, moisture content vs. density log and laboratory bulk density vs. sonic log.

INTRODUCTION

The Downhole Geophysics Research Project was undertaken as a joint venture by coal and oilsands mining operators, consultants, geophysical companies, research organizations and government agencies. From 1986 to 1990, the feasibility of determining geotechnical and other parameters from downhole geophysical logs in overburden formations was assessed and a number of empirical correlations were developed. This paper is about geotechnical parameters, the approach used to ensure data consistency and the procedures adopted to establish correlations with various geophysical logs. Data were obtained from coal overburden at two locations in Alberta - Highvale Mine, an operating mine with a coal production of about 14 mta located 80 km west of Edmonton, and a coal prospect at Big Valley 100 km northeast of Calgary.

OBJECTIVE

The objective was to identify and refine methods that will improve the collection of geotechnical data for coal mines in western Canada. This would be accomplished if geotechnical parameters could be reliably predicted from geophysical logs. Benefits would thus accrue from an increase in quantity of data as well as a reduction in collection costs.

AVAILABLE DATA

Geotechnical and geophysical data from both sites were obtained from drillholes put down through overburden overlying the coal measures. The regional overburden materials are composed of gently dipping sequences of mudstones, siltstones and sandstones of Upper Cretaceous and Tertiary age. Overlying this succession are Pleistocene deposits consisting of clay till containing ice thrusted blocks of Tertiary rock. Total overburden thickness varies to about 50 m in the areas studied. Montmorillonite, an expansive clay which can jeopardize pitwall stability, is a common clay mineral at both sites, particularly in the bentonitic units. All geophysical logs were run in drillholes from which geotechnical samples were recovered.

GEOTECHNICAL DATABASE

The geotechnical data used in the study were retrieved both from in-house files and from the computerized database maintained by TransAlta Utilities Corporation, owner of Highvale Mine. The database contains data from over 400 drillholes. The test parameters used were derived from the following geotechnical tests:

- natural moisture content
- liquid and plastic limits
- bulk density
- uniaxial compression
- grain size
- triaxial

GEOPHYSICAL DATABASE

Geophysical logging of all geotechnical drillholes was conducted by BPB Instruments who produced the following logs:

- Gamma (API)
- Caliper (cm)
- Long Spaced Density (sdu)
- Bed Resolution Density (sbrdu)
- Linear Density (gm/cc)
- Focussed Electric (ohm-m)
- Short Sonic (micro-sec/m)
- Medium Sonic (micro-sec/m)
- Long Sonic (micro-sec/m)
- Short-Spaced Neutron (snu)

All holes were logged uncased with water as the drillhole fluid.

METHODOLOGY

GEOTECHNICAL

Cross-plots of the geotechnical data were generated to confirm consistency of the data. An example of the good correlation between plasticity index and liquid limit for the Highvale data is shown on the Plasticity Chart where the bestfit line through the data points has a correlation coefficient essentially equal to unity (Fig. 1). The triangular plot of three classification test parameters (Fig. 2) shows the overburden materials exhibit, relative to the variation in natural water content, a large range in plasticity index and clay fraction which is indicative at this site of materials with variable bentonitic contents.

Adjustment of the core depths was found to be necessary, however, to improve correlations between geotechnical parameters and geophysical logs. The approach adopted took advantage of the fact that both extremely hard sandstone lenses (hardbands) and weak bentonitic seams are present in the overburden formations. These strata not only were extensively sampled geotechnically but also exhibited

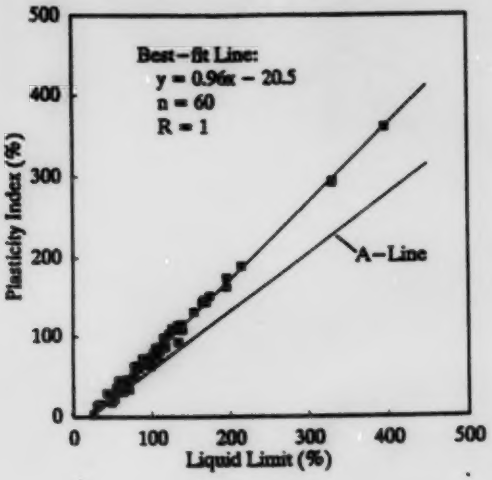


Figure 1. Plasticity Chart

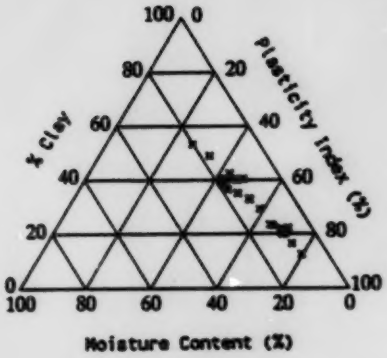


Figure 2. Classification Parameters

pronounced sonic log signatures. By selecting samples with uniaxial compressive strengths greater than 10 MPa and plotting the digitized short sonic log readings over a depth interval 0.5m above and below the recorded sample depth, it was possible to realign the sample with the characteristic trough or low point on the sonic signature as indicated on Fig. 3. A similar approach was used for very low strength (less than 2 MPa) bentonitic seams except that the sample was aligned with the peaks or high values on the short sonic curve. Depth corrections were generally not possible for specimens having compressive strengths intermediate between 2 and 10 MPa since a characteristic peak or trough on the curve was rarely present. The magnitude of depth corrections applied to uniaxial compression test samples varied from 0 to a maximum of 0.7m as depicted on Fig. 4.

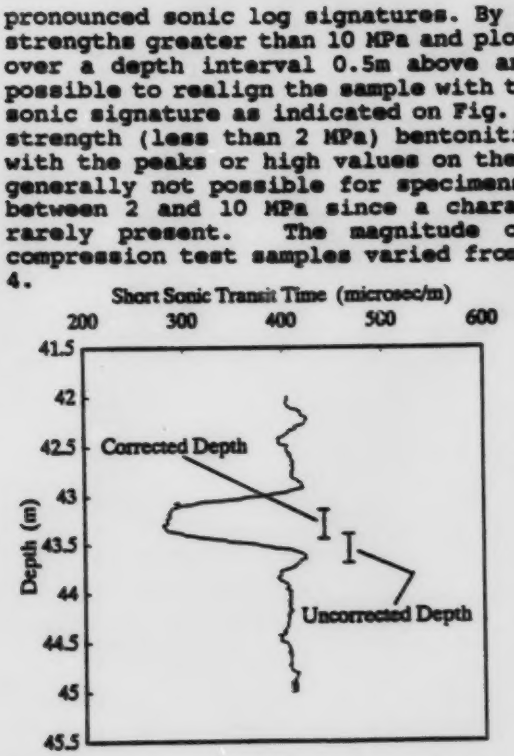


Figure 3. Typical Depth Correction

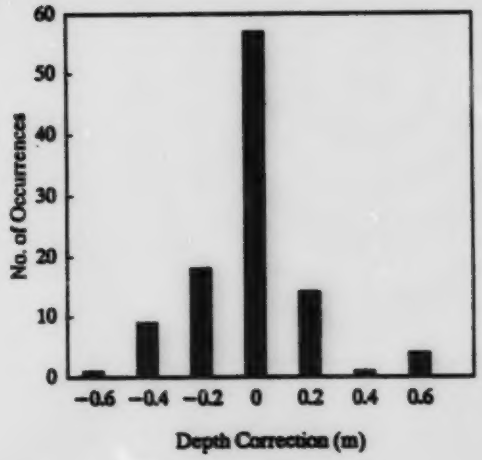
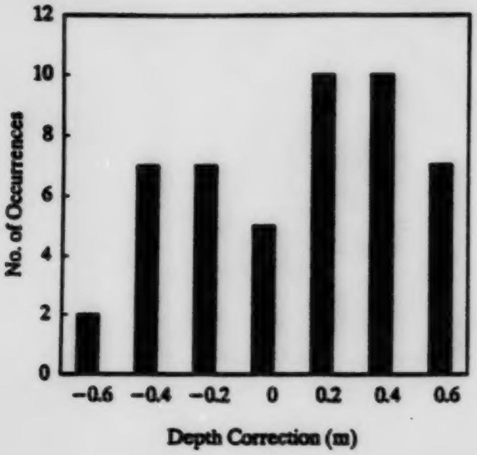


Figure 4. Corrections based on sonic log

A second method of core depth alignment was used in which the laboratory-determined sample bulk density and linear density log values were compared to obtain the depth of best match. A histogram of depth corrections applied on a density log basis is illustrated on Fig. 5. This procedure resulted in enhanced correlations especially between moisture content and density logs. The correlation coefficient, R, increased from about 0.8 for unadjusted data to 0.96 after sample depth alignment (Fig. 6). For correlations with the uniaxial compressive strength, average values of each of the sonic logs (short, medium and long sonic) were used for samples having strengths less than 10 MPa, whereas minimum sonic values were used for samples with strengths greater than 10 MPa.



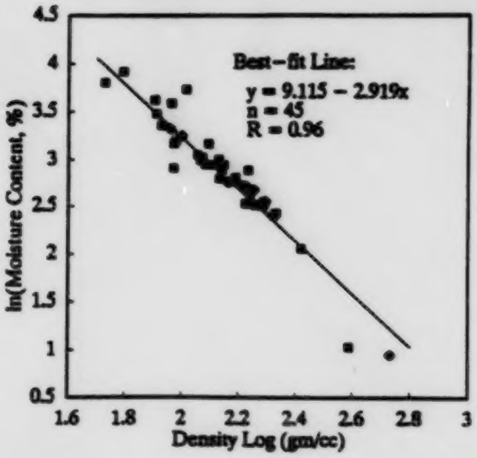


Figure 5. Corrections as per density log

Figure 6. MC vs density log

For all other correlations, the various geophysical logs over depth intervals corresponding to the corrected geotechnical sample depths were downloaded from the database and the average, maximum and minimum values were in turn correlated with each geotechnical parameter.

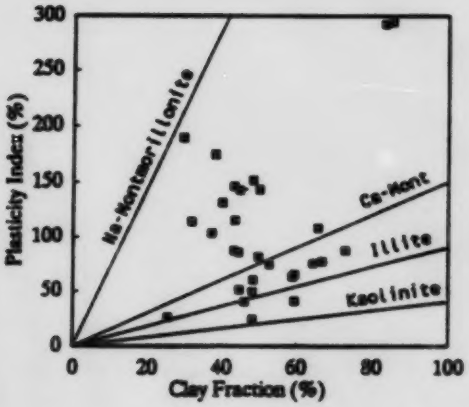
GEOPHYSICAL

Based on cross-plots conducted early in the study, it was determined that individual geophysical logs did not require depth adjustment with respect to other logs. In addition the standard 9m/min logging rate was found to be satisfactory for correlation studies and did not need to be reduced.

CORRELATIONS

After compilation and editing in tabular form, the geotechnical and geophysical parameters were correlated using the linear regression procedures in the Lotus 1-2-3, version 3.x, computer program.

In addition, a few cross-plots of geotechnical parameters were prepared to illustrate the degree of consistency within the data set. These plots included the Plasticity Chart (Fig. 1) and 3-parameter plot (Fig. 2) discussed previously as well as the Activity Chart (Fig. 7), a graph of specimen dry density vs. moisture content (Fig. 8) and finally a plot of uniaxial compressive strength vs. secant modulus (Fig. 9).



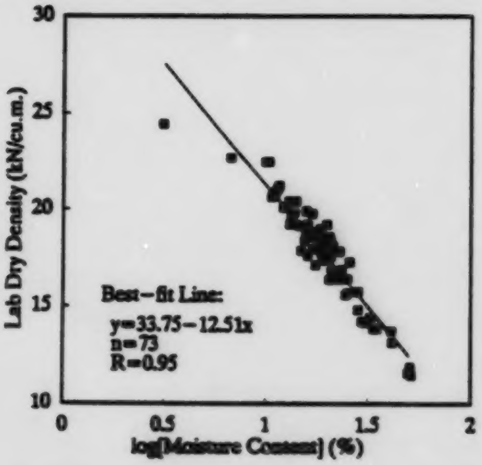


Figure 7. Activity Chart

Figure 8. Lab moisture-density curve

The Activity Chart for Highvale formations (Fig. 7) indicates a wide range in clay mineral composition encompassing both sodium and calcium montmorillonite as well as illite and kaolinite. The relatively high concentration of sodium montmorillonite denotes a potentially active material with an affinity for water and a potential for high change in volume with change in moisture content. The effect of variable montmorillonite content in the geologic formations on geophysical log responses is difficult to predict.

The relationship between dry density and moisture content determined in the laboratory from representative core samples shows a good correlation on a log-normal plot (Fig. 8). Another interesting, if not unexpected, relationship is the very good correlation between the uniaxial compressive strength and the secant modulus shown on Figure 9. The secant modulus is defined as the ratio of the compressive strength to the strain required to cause failure, i.e. the slope of the line extending from the origin to the point of failure on the stress-strain curve.

The geophysical data for the desired geotechnical sample depth intervals were downloaded from the VAX database and manipulated to obtain the maximum, minimum and average values for each log and depth interval. Upon tabulating and aligning with the geotechnical data in a Lotus 1-2-3 spreadsheet, the correlation procedure commenced.

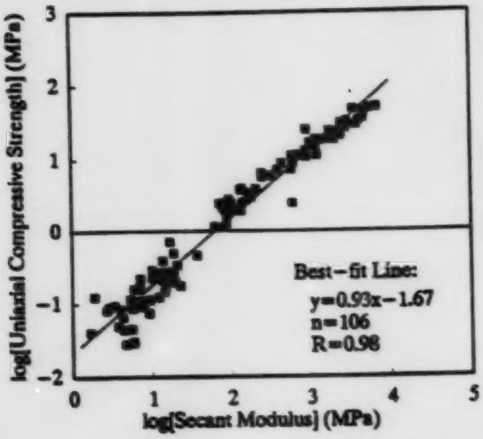


Figure 9. Q_u vs Secant Modulus

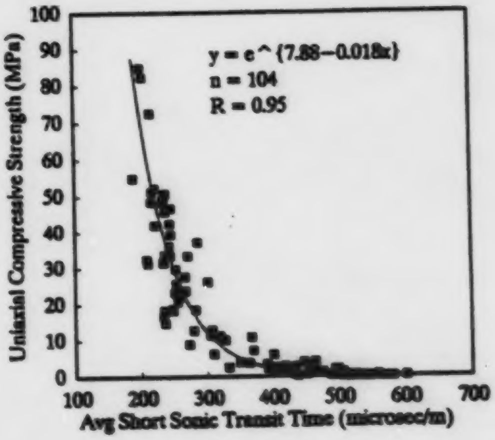


Figure 10. Q_u vs sonic log

REGRESSION ANALYSES

With the coefficient of correlation, R, used as an indicator, a significant number of satisfactory (R = 0.7 to 0.8) to very good (R = 0.9+) correlations were obtained from the regression analyses conducted. Most correlations were derived from linear regression analyses, although two relations were obtained manually from curvilinear analysis. A summary of satisfactory correlations is given in Table 1.

The good correlation between uniaxial compressive strength and short sonic transit time is illustrated on Fig. 10 and comparable relations by other investigators are shown on Fig. 11. Data on concrete cores tend to support the relationship from the present study (Fig. 12).

The usefulness of the sonic log-compressive strength relationship becomes apparent when preparing maps of the occurrence of hardbands and other difficult-to-dig strata prior to mining. Whether a material is diggable or not depends not only on the digging capability of the stripping equipment but also on the formation strength (O'Regan et al, 1987; Wade et al, 1987; Wade et al, 1988; Wade, 1989). Since strength data from core samples rarely provide sufficient areal coverage to permit other than rudimentary mapping, sonic logs, which are generally run in both cored and uncored holes, can be used to provide additional strength data and thus significantly improve areal coverage. The development of

Table 1. Summary of satisfactory correlations

Parameter y	x	Equation Obtained	n	R
Bulk Density	Nt	$y = 1137 + 0.48x$	127	0.78
Bulk Density	LSD	$y = 2605 - 0.44x$	88	0.75
Bulk Density	LD	$y = 1.043 - 0.108x$	46	0.98
Bulk Density	SS	$y = 3180 - 2.1x$	120	0.81
Bulk Density	log(SS)	$y = 7434 - 1969x$	120	0.79
log(Bulk Density)	SS	$y = 3.53 - 0.00004x$	120	0.80
Moisture Content	SS	$y = 0.3x - 27.2$	121	0.76
Moisture Content	S-wave	$y = 20.67 + 0.01x$	14	0.96
ln(MC)	LD	$y = 9.12 - 2.92x$	45	0.96
ln(MC)	LD	$y = 9.80 - 3.33x$	128	0.77*
loglog(MC)	log(RES)	$y = 0.68 - 0.61$	123	0.77
ln(MC)	ln(Nt)	$y = 33.7 - 4.07$	127	0.79
% Clay	LD	$y = 203 - 74x$	43	0.79
ln(% Clay)	LD	$y = 8.06 -2.03x$	43	0.84
Q_u	SS	$y = e^{(7.88 - 0.018x)}$	104	0.95
Q_u	SS	$y = 153 - 0.65x + 0.0068x^2$	104	0.89
ln(Q_u)	ln(SS)	$y = 38.42 - 6.35x$	104	0.94
Q_u	LS	$y = e^{(7.31 - 0.015x)}$	59	0.87
ln(Q_u)	ln(LS)	$y = 32.04 - 5.10x$	59	0.85
Q_u	log(RES)	$y = 52.8x - 49.2$	92	0.77
Q_u (sandstone)	log(RES)	$y = 26.4x - 54.5$	44	0.87
Secant Modulus	SS	$y = 17394 - 65.2x + 0.61x^2$	85	0.84
ln(Sec Mod)	SS	$y = 6.72 - 0.0104x$	85	0.86

* Correlation coefficient prior to sample depth correction

Legend:

Bulk Density = lab determined bulk density (gm/cc)
e = base of natural logarithms
LD = Linear Density Log (gm/cc)
ln = natural logarithm
log = common logarithm
Log = geophysical Log
LSD = Long Spaced Density Log (sdu)
LS = Long Spaced Sonic Log (microsec/m)
MC = moisture content, % of dry mass
n = No. of observations
Nt = Neutron Log (snu)
Q_u = uniaxial compressive strength (MPa)
R = coefficient of correlation
RES = Focussed Resistivity Log (ohm-m)
Sec Mod = secant modulus (MPa)
SS = Short Spaced Sonic Log (microsec/m)
S-wave = Shear Wave Transit Time (microsec/m)
% Clay = % of particles smaller than 0.002mm

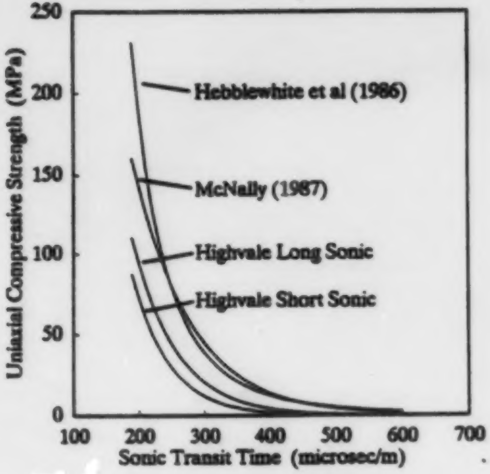


Figure 11. Comparative relations

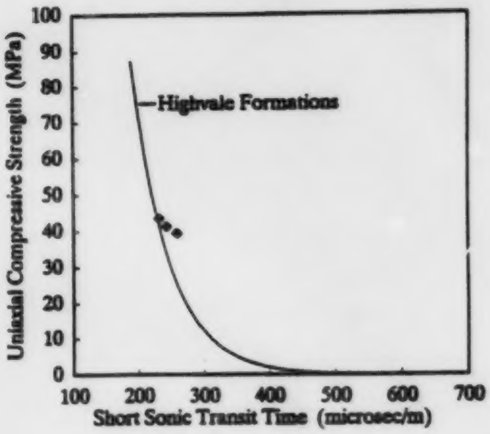


Figure 12. Tests on 80-yr old concrete

a Scanning Routine for scanning digitized sonic logs to ascertain the depth and thickness of undiggable strata further enhances the mapping procedure (Wade and Peterson, 1991).

Correlations between the strength parameters c and ϕ, which are conventionally determined directly from triaxial and direct shear tests for use in pitslope stability analyses, and various geophysical logs are not readily established. However, an approach which may have some merit is to establish an algorithm empirically relating the c term to the uniaxial compressive strength. For example, Underwood & Dixon (1976) showed that the c/Q_u ratio for intact samples of sedimentary rock tested in the triaxial apparatus was equal to about 14%. Since their tests apparently were conducted on a "total stress" basis, i.e. pore water pressures induced by shearing were not measured and back pressure saturation was not applied to the specimens, their findings are not directly applicable to the data set in the present study but the concept has been utilized. Prediction of the locally applicable c and ϕ values for a gradationally variable and spatially extensive siltstone-sandstone unit at Highvale Mine can be achieved by the following procedure:

- Construct upper and lower linear envelopes which encompass the data from consolidated undrained triaxial tests on a plot of major principal stress (σ_1) versus minor principal stress (σ_3) as shown on Figures 13 and 14;

- Establish upper and lower limits for c and ϕ, respectively, by substituting typical values of σ_1 and σ_3 from the upper and lower envelopes into the equation for the Mohr envelope given below:

$$\sigma_1(1-\sin\phi) = 2c(\cos\phi) + \sigma_3(1+\sin\phi) \qquad \text{.... (1)}$$

- Determine the approximate range in Q_u, which for this unit is about 2 MPa to 50 MPa;

- Using the general expression for the linear failure envelopes on Fig. 13 or 14, namely, $\sigma_1 = m\sigma_3 + b$, relate Q_u to the intercept b by the algorithm:

$$b = nQ_u \qquad \text{.... (2)}$$

- Select from a geophysically logged drillhole in the local area being considered the sonic transit time value which represents the siltstone-sandstone unit, obtain the corresponding Q_u value from Fig. 10, evaluate b and m from the proportional Equations 3 and 4, and compute the value of parameters c and ϕ from Equations 5 and 6 below:

$$b = b_{max} - (Q_{u(max)} - Q_u)(b_{max} - b_{min})/(Q_{u(max)} - Q_{u(min)}) \quad .... (3)$$

$$m = m_{max} - (Q_{u(max)} - Q_u)(m_{max} - m_{min})/(Q_{u(max)} - Q_{u(min)}) \quad .... (4)$$

$$b = 2c(\cos\phi) \quad .... (5)$$

$$m = (1+\sin\phi)/(1-\sin\phi) \quad .... (6)$$

Typical values for the parameters as well as a description for the symbols used are given in Table 2. From the tabulated values, the computed c/Q_u ratio varies from 0.4% to about 32% for total stress conditions, and from 0.3% to 13% for effective stress conditions. The reason for the relatively wide range of computed ratios, as well as the variance from values reported by Underwood & Dixon (1976), is not clear, but contributing factors may be the varying bentonite content in the specimens tested and the effects of specimen saturation on the bentonite present.

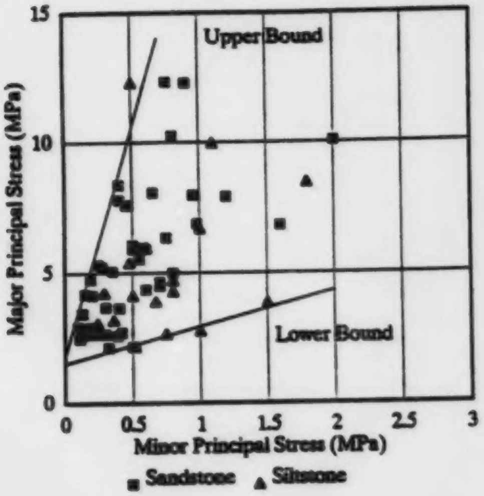


Figure 13. Total stress envelopes

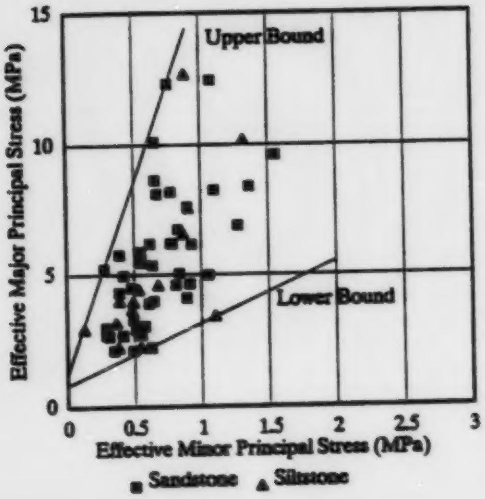


Figure 14. Effective stress envelopes

Table 2. Empirical coefficients relating various strength parameters for sandstone & siltstone

Envelope	Failure Type	m	b	Q_u	n	c	ϕ
Upper	Total stress	17.57	1.7	50	0.03	0.20	63
Lower	Total stress	1.4	1.5	2	0.75	0.63	10
Upper	Effective str.	14.67	1.2	50	0.02	0.16	61
Lower	Effective str.	2.35	0.8	2	0.40	0.26	24

Legend:

m = slope of the linear envelope on σ_1 vs σ_3 plot
b = intercept on σ_1 axis of above plot
Q_u = uniaxial compressive strength, MPa
n = b/Q_u
c = cohesion intercept of the Mohr envelope, MPa
ϕ = angle of internal friction, degrees
σ_1 = major principal stress in the triaxial test
σ_3 = minor principal stress in the triaxial test

Geophysical logs which show promise in predicting geotechnical classification parameters for overburden include linear density, neutron and sonic logs. After depth corrections have been applied, for example, the linear density log correlates well with the bulk density determined in the laboratory (Fig. 15) and reasonably well with the moisture content (Fig. 6) and the clay fraction (Fig. 16). With no depth correction applied, the correlation coefficient for the moisture content-linear density relation reduces from 0.96 to 0.77 (Table 1). For bentonite-rich materials, the relationship between moisture content and shear wave transit time as computed from sonic logs appears to be consistent with published data (Fig. 17).

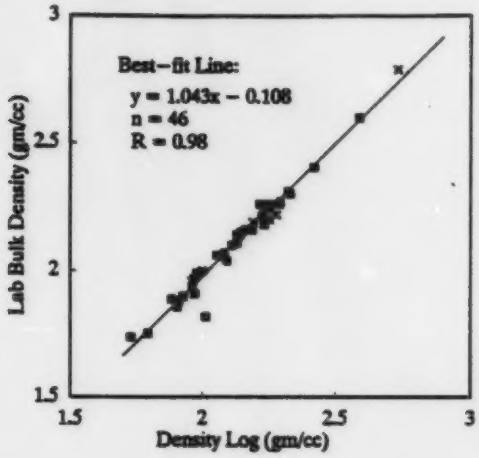


Figure 15. Lab density vs density log

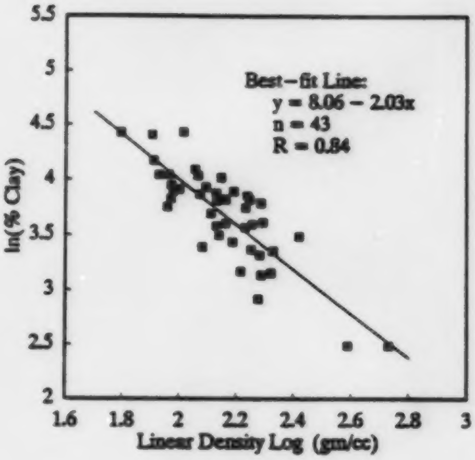


Figure 16. % clay vs density log

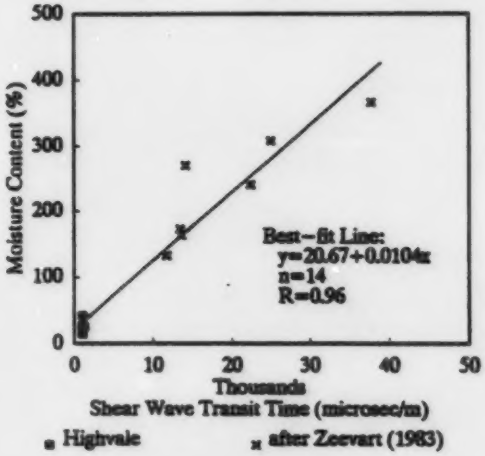


Figure 17. Moisture Content vs shear wave transit time for bentonitic materials

CONCLUSIONS

From the results of the study, it was concluded that, by depth aligning geotechnical core samples with the corresponding geophysical logs, a number of different geotechnical parameters can successfully be correlated with individual logs. Some enhancement of the correlation is often possible when groups of logs are used. All of the satisfactory correlations obtained, however, would be considered more reliable if, by increasing the number of data points, the generated correlation coefficients were not materially reduced.

Although correlation coefficients are sometimes enhanced by using logarithmic functions of the parameters, the procedure may actually de-sensitize the resulting relationship thereby diminishing its effectiveness as a predictive expression.

Additional work needs to be done to determine whether the strength parameters, c and ϕ, as well as other important geotechnical parameters, such as Modulus of Elasticity, Poisson's Ratio, coefficient of consolidation, to name a few, can be correlated directly with geophysical logs. The effects of carbon content in carbonaceous overburden strata on geophysical log response, and thus on geotechnical parameter correlations, should also be studied further.

ACKNOWLEDGEMENTS

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3

COAL SCIENCE

PAPERS AND ABSTRACTS

NOTES

COALBED METHANE POTENTIAL OF SELECTED KOOTENAY COALS IN RELATION TO PETROGRAPHIC AND MINERALOGIC CHARACTERISTICS

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High-rank coals of the Rocky Mountain Front Ranges in southeastern British Columbia are generally believed to have a high coal bed methane potential. The aim of the present study is to contribute to the understanding of the role of maceral and mineral compositions relative to gas production and absorption capacity of seams of the Jurassic-Cretaceous Kootenay Group.

For this purpose, 51 core and drill cuttings samples from four wells were examined using following techniques: gas desorption tests, vitrinite reflectance measurements, quantitative maceral and microlithotype analyses and semi-quantitative mineralogical analyses of low temperature ashes.

The gas desorption capacities of the samples were found to vary largely as a function of shale content, structural position and hydrodynamics at well sites. The petrographic results allowed ranking of the coals as medium-to low-volatile bituminous. Maceral group contents varied according to the stratigraphic position of the seams, i.e. decrease of vitrinite and increase of inertinite, mainly semifusinite, towards the base of the section. Highly disturbed sections contained crushed (sheared) vitrinite. The microlithotypes are dominated by vitrite and inertite. The mineral fraction is dominated by quartz with subordinate carbonate and clay minerals.

The preliminary results suggest that coals rich in inertinite macerals have a relatively high gas storage capacity, whereas coals rich in vitrinite macerals have lower storage capacity. High shale or mineral contents (with the exception of kaolinite and dolomite) correspond negatively to the desorption results, however, subtle trends in coal bed methane potentials related to the petrographic characteristics apparently are masked by factors such as structural setting, shale content and hydrodynamic conditions.

Further investigations on the porosity of the partly sheared coals as well as detailed work on the diagenetic mineralogy and paragenesis are needed to clarify the gas storage capacity of the Kootenay coals.

NOTES

CHARACTERIZATION OF COALS FROM THE WHITEHORSE TROUGH, YUKON TERRITORY

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ABSTRACT

Coal deposits from the Whitehorse Trough are studied to evaluate rank, petrography and geochemistry. Coals from Mt. Granger were intruded by rhyolite sills and are coked. Division Mountain coals contain the greatest amount of liptinite (13% mmf), least amount of vitrinite (51% mmf) and are the in lowest rank (Ro$_{max}$ 0.6%). The Carmacks coals show a rank range (Ro$_{max}$ from 0.76% to 1.2%); vitrinite and liptinite average 70% mmf and 5% mmf respectively. Ash in the Mt. Granger coal averages 48%. Division Mountain coals average 21%, whereas the Carmacks area coals show a wide range of ash contents ranging from 14% to 43%. Sulfur is low in all deposits (<0.4%) and concentrations of undesireable elements, eg. As, Cl, B, U, Pb and Zn are low. Increased concentrations of Ca, S, Br and Cl occur in the coals relative to partings. The intrusions within Mt. Granger coals contain elevated Fe, Mg, Ti, Cr, Co, Mn and V; Cr, Ni and Zn show increased concentrations in the coal in this area. Rank and petrography suggest favourable utilization potential for the Division Mountain and Carmacks deposits. High ash and rank limits the potential of the Mt. Granger deposit.

INTRODUCTION

With increasing demand for energy in Canada's northern region, coal is once again being investigated for utilization potential. Coal deposits in Yukon Territory are being studied to assess petrographic and geochemical composition for potential use in thermal power generation and coalbed methane production.

The Whitehorse Trough, located in south-central Yukon, contains numerous coal occurrences (Ricketts, 1984; Milner and Craig, 1973; Campbell, 1967). Of these, three areas are proximal to existing populations and established infrastructure and are believed to contain significant coal resources. Coal occurrences within these deposits have been partially investigated and chemical characteristics such as ultimate and proximate analyses have been examined. To date, limited petrographic and geochemical work has been completed but information regarding the full potential of these deposits has not been gathered and evaluated.

In this report, rank, petrographic and geochemical characteristics of coals within these deposits is investigated. These parameters are used as preliminary indicators of coal quality and coalbed methane potential.

GEOLOGICAL BACKGROUND AND STUDY LOCATION

The Whitehorse Trough (Figure 1) contains a thick sequence of rocks reflecting the development and infilling of a fore-arc basin (Templeman-Kluit, 1979). Rocks within the Whitehorse Trough (Table 1) include Triassic basalts and volcanic detritus and carbonate reef deposits along the trough margin (Lewes River Group). Yukon strata of Jurassic age record the deposition of submarine fans progressing into deltaic and alluvial-fluvial deposits reflecting the transition from marine to non-marine conditions (Lower and Upper Laberge Group respectively). By the Upper Jurassic - Lower Cretaceous, the final stages of closure and uplift of the Whitehorse Trough resulted in the deposition of a molasse sequence that includes coarse clastics, shale, mudstone and coal deposited in alluvial fans and braided streams (Tantalus Formation) (Long, 1987). Thin coals are present in the Lower Laberge Group; thicker coals are present in the Upper Laberge and in the Tantalus Formation. Seams are typically found within relatively thin shale / mudstone lithologies that occur between thick conglomeratic units. The coal horizons generally have a limited lateral extent possibly attributable to a high energy depositional environment and/or post depositional folding and faulting. Strata of the Whitehorse Trough are overlain and intruded by younger volcanic rocks (Upper Cretaceous Carmacks Group volcanics) (Lowey and Hills, 1988).

TABLE 1 General Stratigraphy (from Wheeler, 1961)

	Upper Jurassic - Lower Cretaceous	Tantalus Fm. (1000 m avg. thk.)
MESOZOIC	Upper - Lower Jurassic	Laberge Group (3000 m avg. thk.)
	Upper Triassic	Lewes River Group (3000 m avg. thk.)

Three locations within the Whitehorse Trough contain thick coal deposits of potential interest (M.I.R. 1973, 1975). The deposits occur southwest of Whitehorse (at Mt. Granger), west of Braeburn (at Division Mountain) and at Carmacks (Figures 1 and 2). The first reported coal occurrences in Yukon were made by Dawson (1887) in the Carmacks area. Further work was conducted by McConnell in 1908 at Mt. Granger, and by Cairnes (1907) at Division Mountain.

Coal was mined north of Carmacks at Tantalus Butte from 1923 until 1938 and sporadically until 1967. Cypress Anvil Ltd. operated underground workings from 1968 until 1978 when fire closed the underground mine; surface exploration and mining occurred between 1975 and 1985. Underground mining at Tantalus, southeast of Carmacks, was performed sporadically from 1903 to 1922. Exploration (including

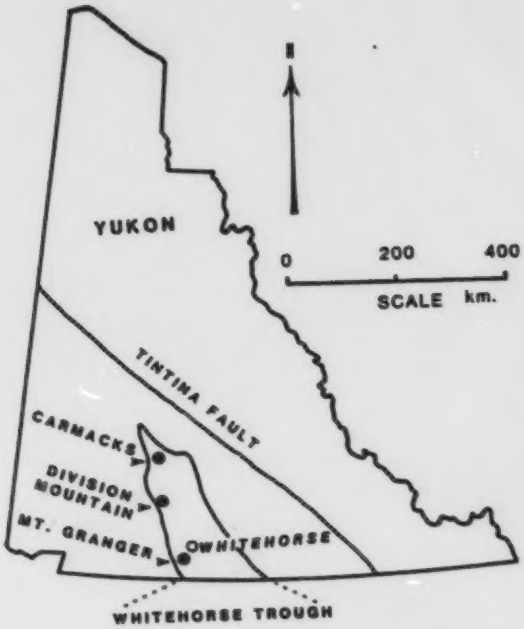
N
YUKON
0
200
400
SCALE km.
TINTINA FAULT
CARMACKS
DIVISION MOUNTAIN
MT. GRANGER
WHITEHORSE
WHITEHORSE TROUGH

FIGURE 1 LOCATION MAP SHOWING SAMPLING LOCATIONS

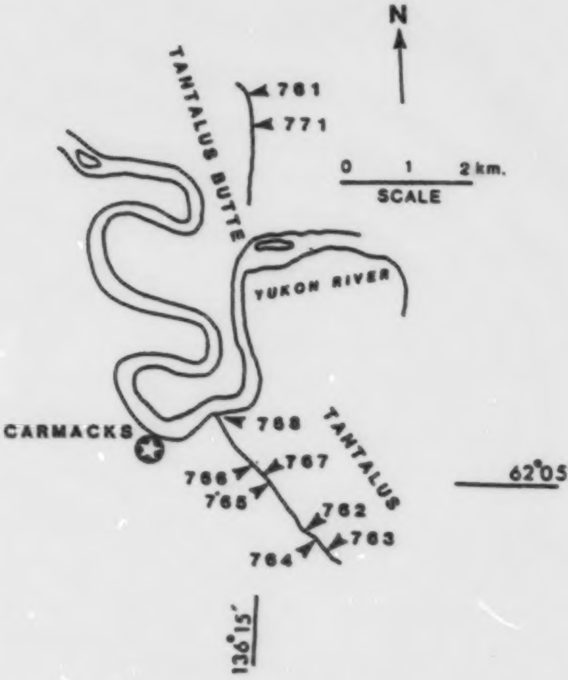
N
TANTALUS BUTTE
761
771
0
1
2 km.
SCALE
YUKON RIVER
CARMACKS
768
TANTALUS
767
766
765
762
763
764
62°05'
136°15'

FIGURE 2 LOCATION OF TRENCHES SAMPLED IN THE CARMACKS AREA, YUKON.

drilling and trenching) southward along seam strike has been performed sporadically by various companies from 1966 to 1979.

The other two deposits have been under investigation since 1972 at Division Mountain by Arjay Kirker Res. Ltd. and Archer Cathro Ltd., and at Mt. Granger since 1982 by Whitehorse Coal Corp.

METHODOLOGY

Sample Locations and Descriptions

1) Whitehorse area - Mt. Granger

The Tantalus Formation at Mt. Granger contains up to 8 seams, two of which are thick and of economic interest (zones A and B, Perry, 1984). Coal is interbedded with carbonaceous mudstone, and is often scoured by thick conglomerates (Bremner, 1989). The main coal bearing zone (zone B) exposed in the "Main Pit" of Whitehorse Coal Corp. was sampled (sample 757). The seam is 4.5 m thick, dips 30 - 50° north, and has undergone faulting and folding (Figure 3). The coal may be confined or thickened in the axial zone of a large drag fold (Long, 1987; Bremner, 1988). Rhyolite sills have intruded the seam, producing a high-ash, natural coke (Goodarzi and Jerzykiewicz, 1989).

2) Braeburn - Division Mountain

Fifteen seams have been encountered in drillholes and trenches in the Laberge Group near Division Mountain, above the Nordenskiold River Valley. The coal outcrop dips 70° southwest in what is thought to be a limb of a syncline (Bostock, 1936; Carne, 1990). The main coal bearing unit was sampled (sample 760); this zone is 15 m thick, with three main seams separated by two partings, 1 and 0.5 m thick (Figure 4).

3) Carmacks area - Tantalus and Tantalus Butte

A coal-bearing zone within the Tantalus Formation occurs on the north (Tantalus Butte, Figure 5) and the south (Tantalus, Figure 6) side of the Yukon River at Carmacks. The coal bearing zone consists of three seams, 2.5 m, 2 m and 1 m, separated by partings of variable lateral thickness averaging 1 m.

The north (trench 761) and south end (trench 771) of the Tantalus Butte open pit were sampled (Figure 2). The coal zone dips approximately 50° west (Bostock, 1936), and has been deformed by faulting and folding.

Coal on the south side of the Yukon River at Tantalus was exposed along strike and sampled in seven trenches (Figure 2). The dip of the zone ranges from 50° east to almost vertical, as the zone occurs within a tight syncline - anticline pair (Bostock, 1936; M.I.R., 1971, 1972, 1973).

Analytical Procedures

Seams at each location were sampled from top to bottom as plys based on differences in lithology (i.e. sheared, mineral-rich, partings, brightness) or in 50 cm. intervals if lithology appeared consistent. Trenches 764, 765 and 767 at Tantalus (Figure 2) were sampled as whole-seam composites. Samples were ground to -20 mesh for petrographic analysis, and to -100 mesh for geochemical analysis.

The -20 mesh split was mounted in an epoxy pellet and then ground and polished for microscopy study as per the method outlined in Stach et. al., 1975. Maceral composition was determined by point counting under oil immersion conditions with white and UV reflected light. Rank was determined by measuring maximum (Ro_{max}) and minimum (Ro_{min}) reflectance on vitrinite as per I.C.C.P. 1971 and 1975 methods.

Splits of -100 mesh coal were analysed as follows: a) ash, sulfur, moisture, fixed carbon and volatile matter was determined on whole coal as per A.S.T.M. 1979 standards. b) whole coal elemental composition was determined by instrumental neutron activation, atomic absorption and D.C. plasma spectroscopy methods. c) semi-quantitative mineralogy of selected samples was determined by x-ray diffraction on low-temperature ash (<125°C) as described by Mitchell and Gluskoter, 1976.

RESULTS

Coal Quality - Rank and Proximate Composition

The coal at Mt. Granger (Section 757, Figure 3) is of anthracite to meta-anthracite rank, (reflectance averaging 6.0% Ro_{max}) due to heating by numerous intrusive sills. Average moisture, ash, volatile matter, fixed carbon and sulfur contents are presented in Table 2. The ash content is variable within the seam, averaging 48.6%. Sulfur is low in the seam, averaging 0.2% (Figure 3).

Division Mountain coal samples (section 760, Figure 4) are of high volatile C to B bituminous, as indicated by an average reflectance of 0.6% Ro_{max}. Ash contents are low to moderate, averaging 21%. Volatile matter and fixed carbon contents of 45.8 and 64.2 %, (D.A.F.), substantiate the rank as based on reflectance. Sulfur is low, averaging 0.4%.

The Tantalus Butte samples (sections 761 and 771, Figure 5) are very similar in rank and proximate composition. The coal is high volatile B-A bituminous, as shown by a reflectance of 0.76 Ro_{max} and a volatile matter and fixed carbon content of 37 and 63 % (D.A.F.). Sulfur averages 0.25% at these locations.

The Tantalus location shows minor differences in rank and proximate analysis composition from the northerly section (768) southward (sections 766, 767, 765, 762, 764 and 763). All sections from this area are of a medium volatile bituminous rank; however, the reflectance of the 768 section (Figure 6) averages 1.22% Ro_{max} while the remainder of the sections show a range of reflectance from 1.01% to 1.08% Ro_{max}. Volatile matter and fixed carbon contents support a rank of medium volatile bituminous. Sulfur averages 0.3% in the Tantalus sections.

TABLE 2 AVERAGE RANK AND PROXIMATE ANALYSIS COMPOSITION

SECTION AVERAGE	MOISTURE % as rec.	ASH % as rec.	VOLATILE MATTER D.A.F.	FIXED CARBON D.A.F.	SULFUR % as rec.
757	3.7	48.6	15.0	85.0	0.2
760	13.5	21.2	45.8	54.2	0.4
761	6.3	10.8	36.6	63.4	0.3
771	5.1	11.7	37.0	63.0	0.2
768	N.A.	N.A.	N.A.	N.A.	0.4
766	12.3	23.3	35.0	65.0	0.4
767	15	18.5	32.3	67.7	N.A.
765	13.3	14.6	35.5	64.5	0.4
762	11.4	37.1	38.2	61.8	0.3
764	16.5	43.9	58.1	41.9	0.2
763	15.6	14.3	36.1	63.9	N.A.

TABLE 3 AVERAGE PETROGRAPHIC COMPOSITION

SECTION	Ro_{max} %	MINERAL %	VITRINITE % MMF	INERTINITE % MMF	LIPTINITE % MMF
757	5.2	25	71	29	0
760	0.60	15	51	36	13
761	0.76	5	68	27	5
771	0.77	6	72	23	5
768	1.22	9	77	21	2
766	1.04	14	76	17	7
767	1.01	9	76	22	2
765	1.08	6	74	22	4
762	1.05	34	76	20	4
764	1.02	50	72	22	6
763	1.08	4	75	22	3

In the Division Mountain and Carmacks sections, there are minor amounts of the vitrinite (up to 5% of the total vitrinite) in the section profiles that show slightly elevated reflectance and bireflectance (Ro_{max}-Ro_{min}) values compared to their respective seam's average; these higher values were often found in sheared samples. This may be indicative of tectonic strain, migration of heated fluids and/or the effects of heating from intrusives reportedly occurring in these areas.

Moisture content varies significantly amongst the sections (Table 2) and is probably related to rank as well as weathering of the exposures.

Petrographic Composition

Average petrographic composition (macerals and mineral matter) for the sections is summarised in Table 3. The Mt. Granger section consists primarily of vitrinite coke and inertinite char (Figure 7). Mineral matter is high, up to 52%. On a mineral-matter-free-basis (mmf), vitrinite ranges from 60% to 85 %, whereas inertinite ranges from 15 to 40 %. Liptinite is absent in this section; the distribution of vitrinite and inertinite does not show any stratigraphic trend.

The Division Mountain coals (section 760, Figure 8) contain a moderately high liptinite content of 13 % mmf, with vitrinite and inertinite contents averaging 51% and 36% mmf. Vitrodetrinite and vitrinite A are the dominant vitrinite components and are found in approximately equal amounts. Sporinite comprises 60 % of the liptinite. Inertinite is dominated by fusinite, but up to 25 % of the inertinite consists of low-reflecting semifusinite. The concentration of mineral matter decreases up-section (from 23% to 9%), with a concomitant increase in vitrinite concentration (from 38% to 50%). Liptinite and inertinite do not show significant stratigraphic trends with the exception of a slight concentration of alginite and bituminite at the coal zone margins (roof and floor); however these components only occur in trace amounts.

The composition of the coal on an "as received basis" shows a wide variation in the Carmacks sections, which is partially related to variable mineral matter contents (Table 3). When the coals are compared on a mineral matter free basis, however, the sections from Tantalus and Tantalus Butte show a very similar composition. Vitrinite averages 70%, inertinite averages 25% and liptinite averages 5%. Section 761 from Tantalus Butte contains slightly greater amounts of inertinite (27% mmf) than the remaining sections.

In all sections, the maceral distribution and associations are typical of bi- and trimaceralic lithotypes. Vitrodetrinite, inertodetrinite and liptodetrinite are common in the seams, and there is a lack of banding within the coal seams. The nature of maceral associations indicate minor to moderate reworking and mixing of materials in the original peat swamps, possibly overprinted later on by internal mobilization of coal within seams due to tectonic deformation.

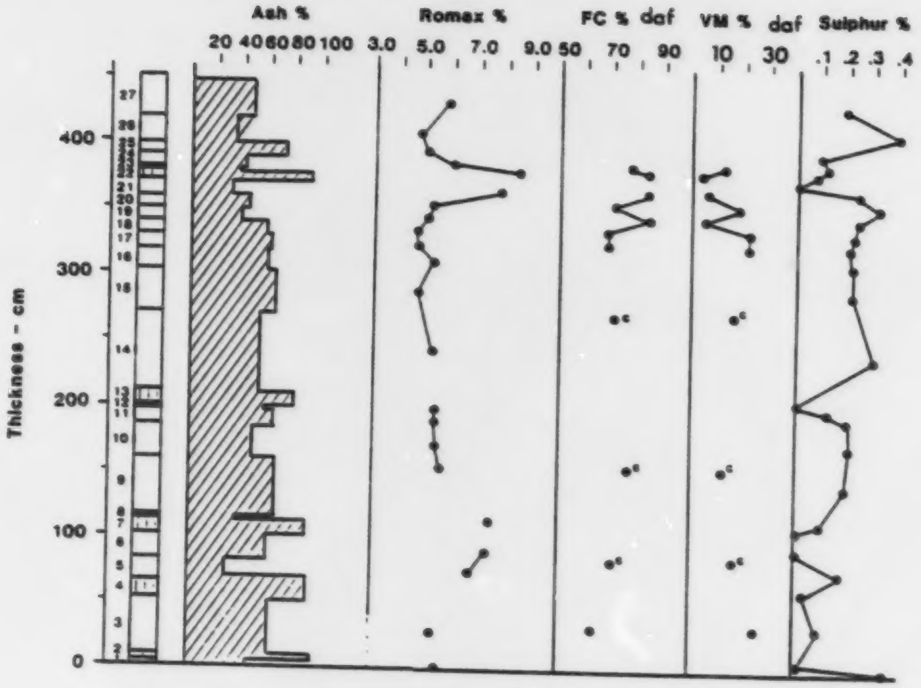

FIGURE 3 MT. GRANGER SECTION PROFILE SHOWING SAMPLES, ASH%, REFLECTANCE, FIXED CARBON (FC), VOLATILE MATTER (VM) AND SULFUR. (DAF -DRY, ASH FREE BASIS). COMPOSITE SECTIONS INDICATED BY "c". Samples 2, 4, 7, 13 and 22 (hash marks) are intrusions).

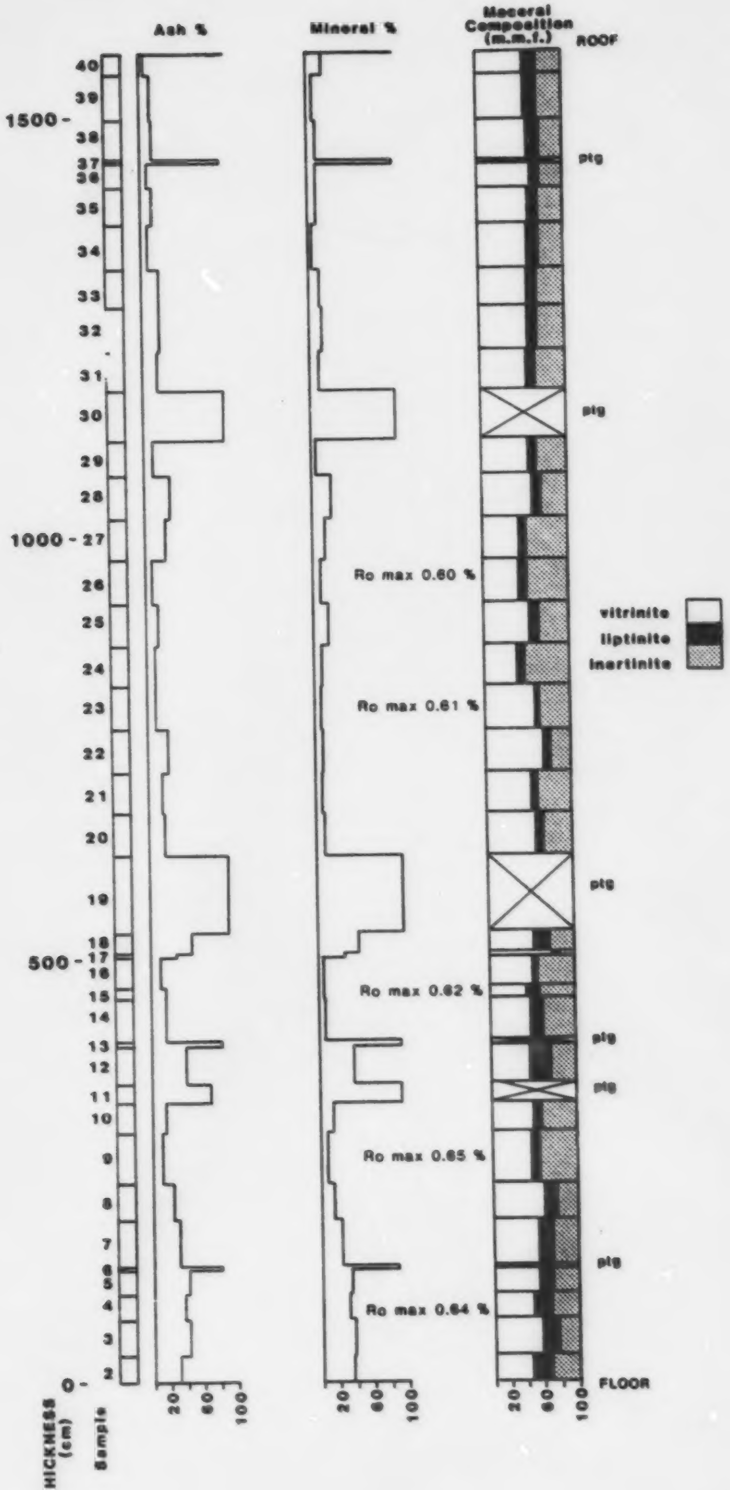

FIGURE 4 DIVISION MOUNTAIN SECTION, SHOWING SAMPLES, ASH%, MINERAL% AND MACERAL COMPOSITION (MINERAL MATTER FREE BASIS, m.m.f.)

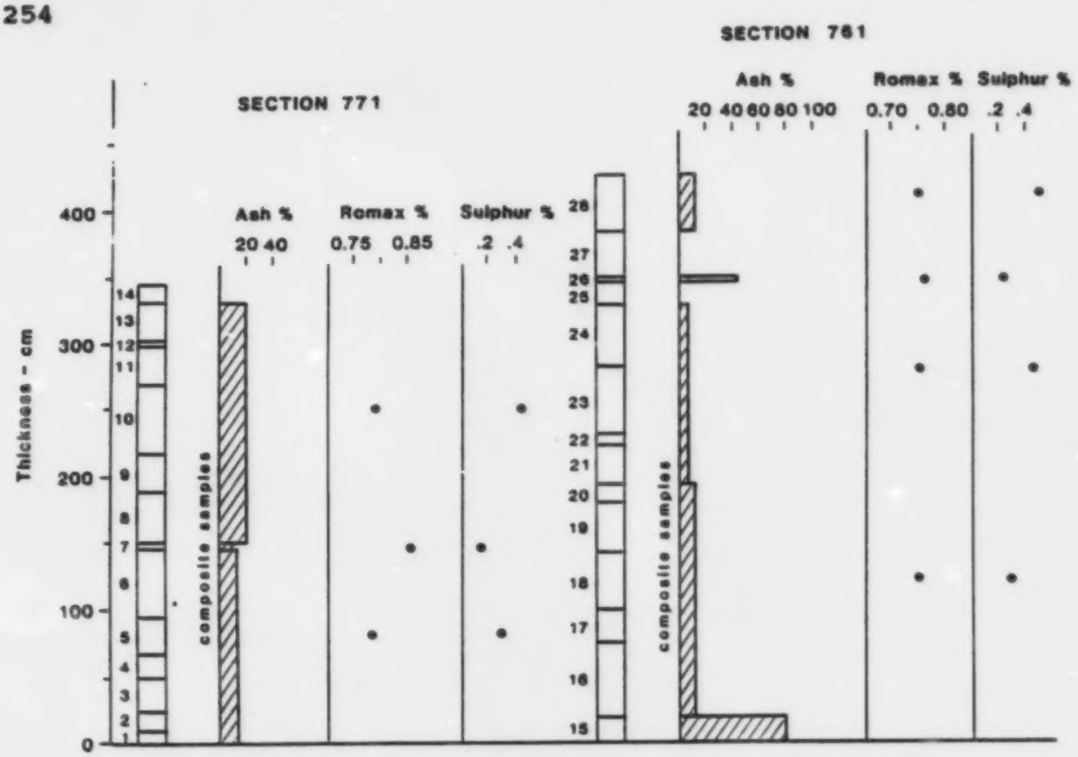

FIGURE 5 TANTALUS BUTTE SECTIONS 771 AND 761, CARMACKS AREA, SHOWING SAMPLE NUMBERS, COMPOSITES ANALYSED, ASH%, REFLECTANCE AND S%.

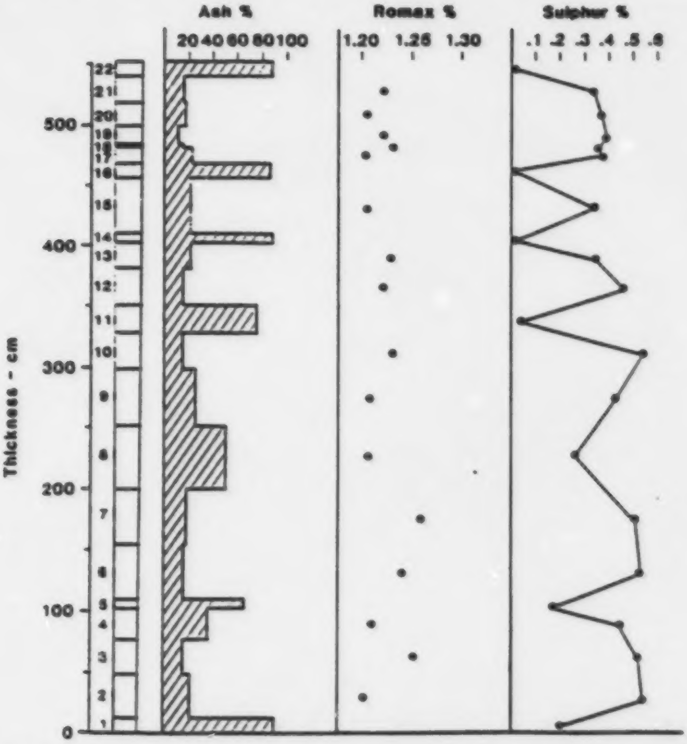

FIGURE 6 TANTALUS SECTION 768, CARMACKS AREA, SAMPLES, ASH%, REFLECTANCE AND SULFUR%.

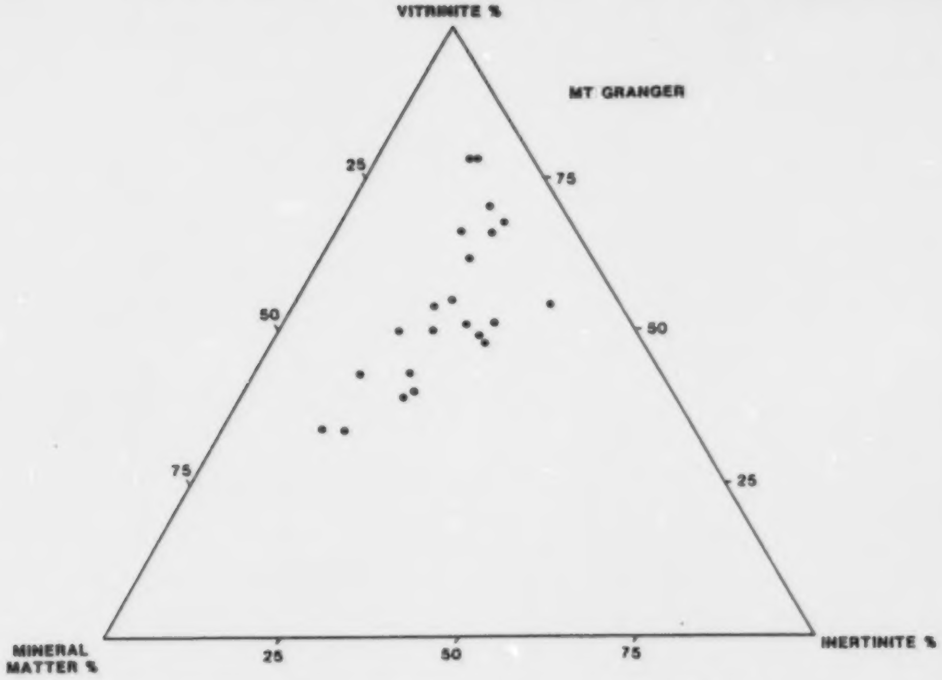

FIGURE 7 MACERAL COMPOSITION ON A MINERAL MATTER FREE BASIS OF THE MT. GRANGER SAMPLES.

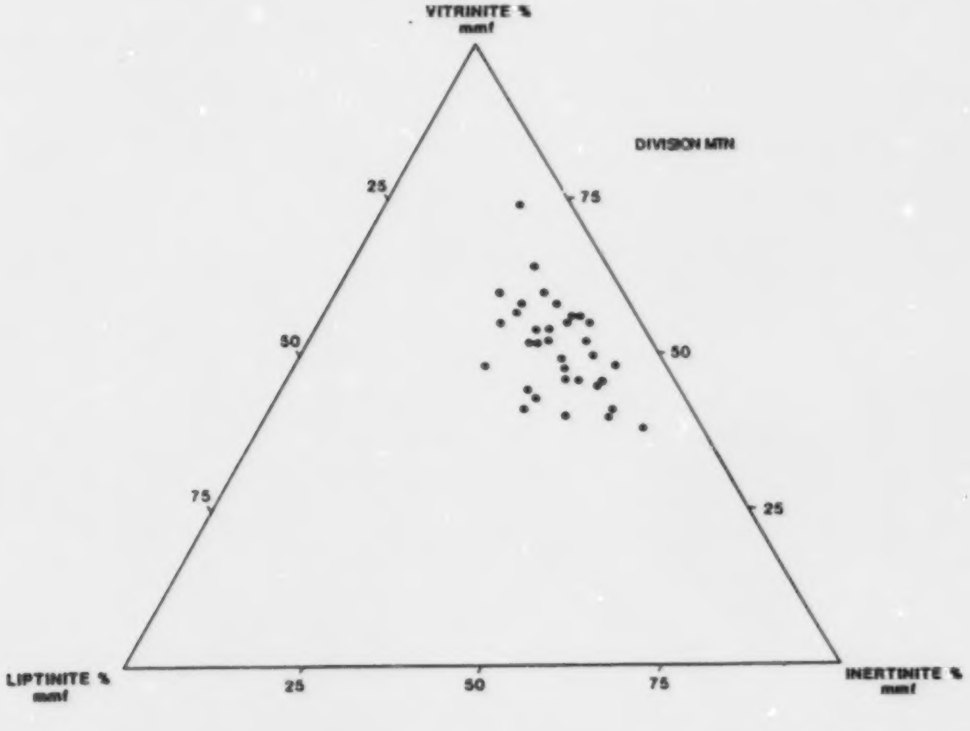

FIGURE 8 MACERAL COMPOSITION ON A MINERAL MATTER FREE BASIS (mmf) OF THE DIVISION MOUNTAIN COAL SAMPLES.

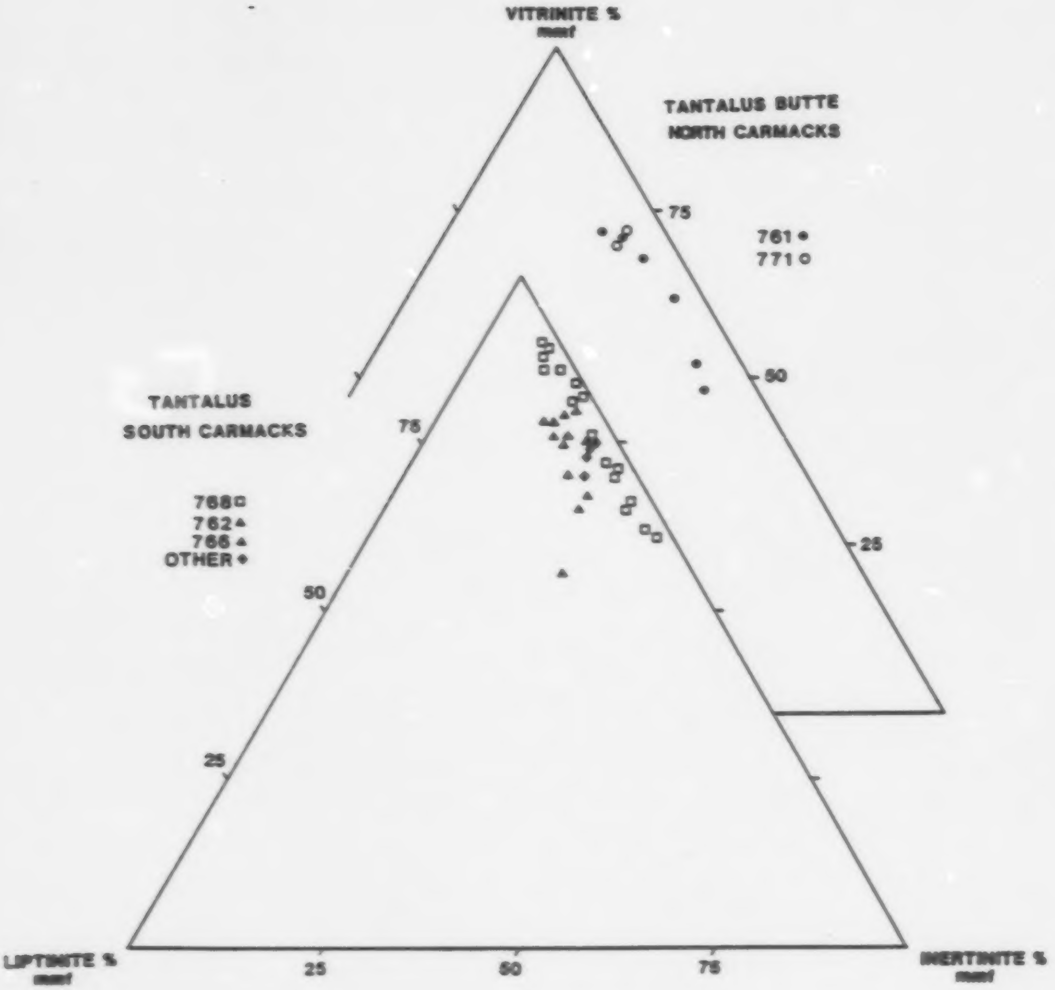

FIGURE 9 MACERAL COMPOSITION ON A MINERAL MATTER FREE BASIS (mmf) OF THE TANTALUS BUTTE AND TANTALUS SECTIONS

Coke Petrography - Mt. Granger Section.

The seam sampled at Mt. Granger (zone B) was intruded by Tertiary rhyolitic sills (Bremner, 1989; Goodarzi and Jerzykiewicz, 1989), resulting in the entire thickness of the coal showing moderate to strong alteration (semicoke to coke). The reflectance profile (Figure 3) shows a regular increase in Ro_{max} towards the intrusions. Medium to fine-grained mosaic was pervasive throughout the seam, with coarse grain mosaic dominant about the uppermost intrusion. The optical texture distribution pattern suggests that the uppermost sill was likely intruded into the coal seam first, allowing the development of a coarse grained mosaic from the liptinite and vitrinite in the seam. The resulting coal would have become devolatilised to an extent, so that upon subsequent intrusions, the lack of volatiles and liptinite would only allow partial plasticity of the coal, resulting in the development of medium and fine grained mosaic textures (Jones and Creaney, 1976).

Two types of inertinite macerals are present; those displaying slight to moderate anisotropy and those which are isotropic. It is likely that the anisotropic inertinites represent semifusinite, which has some reactivity, compared to the isotropic inertinite which represents unreactive fusinite.

Elemental Composition

Major, minor and trace elemental composition of the sections is presented in Table 4-a,b. There are significant differences between the elemental composition of the coal, partings and the intrusions for all sections studied. In general, most elements show greater concentrations in the high ash coals, and greatest concentrations in the partings. Exceptions included Ca, Sr, Br, Cl, C, H, N, O and S, all of which showed increased concentrations in the low-ash coals. The intrusions from Mt. Granger show some unique compositional characteristics; concentrations of Fe, Mg, Ti, Cr, Co, Mn and V are greater than those found in the sedimentary partings and coals. Three anomalously high Zn values (which range from 400-900 ppm) were detected within the Division Mountain section (samples 760-20,-25 and -38). These anomalies are not correlatable to partings or high ash coal; however they may be associated with shear zones or fractures in the coal.

The elemental composition of the coals and partings generally falls within the average composition for coals worldwide as compiled by Valkovic, 1983. Chromium, Cu, Nb Sc and V are found in slightly elevated concentrations; however, the concentrations of these elements are not unusually high.

Mineralogy

Semi-quantitative mineralogy of the low temperature ash from selected samples from Mt. Granger shows a dominance of quartz (up to 70%). Mica, mixed layer clays and kaolinite each average 5%. Anatase, jarosite, goethite and pyrite occur in trace amounts. The intrusions from Mt. Granger are dominated by quartz (86%), kaolinite (10%) and anatase (4%), with traces of pyrite and hematite.

The Division Mountain coals are quartz-rich, averaging 57%. Kaolinite comprises 30% of the low temperature ash,; calcite, gypsum, weddelite and traces of feldspar constitute the remainder of the ash.

The Carmacks area coals show a range of quartz from 30% to 80%. Kaolinite also shows a wide range variation, from 10% to 80%. There does not appear to be a systematic variation in mineralogy amongst the sections from Tantalus Butte and Tantalus; wide ranges in mineralogy are present stratigraphically in each seam section. Exceptions include high concentrations of dolomite (90%) in sample 771-7, and high concentrations of calcite in section 768. These sections contain epigenetic mineral matter in fracture zones; this was verified by optical microscopy observations.

TABLE 4-A AVERAGE MAJOR ELEMENTAL COMPOSITION
(legend at base of Table 4-B)

	757 INT.	768 PTGS	760 PTGS	757 HASH	757 LASH	768 COAL	760 HASH	760 LASH
ASH%	88.5	84.8	84.8	62.0	39.4	18.7	40.6	17.0
S %	0.01	0.01	0.01	0.2	0.2	0.4	0.3	0.3
Al %	12	12	15	9	3	2.6	6.6	3
Ba %	0.04	0.08	0.08	0.09	0.05	0.03	0.04	0.03
Ca %	0.3	0.3	0.03	0.1	0.01	2.2	2.8	2.3
Fe %	5.7	1.4	1.5	1.3	1.0	0.5	0.8	0.8
Mg %	0.7	0.3	0.2	0.1	0.06	0.2	0.4	0.2
K %	0.3	1.3	1.1	0.6	0.2	0.1	0.3	0.1
Na %	0.8	0.07	0.02	0.4	.01	0.03	0.2	0.07
Ti %	1.1	0.7	0.06	0.7	.03	0.2	0.4	0.2

TABLE 4-B AVERAGE MINOR AND TRACE ELEMENTAL COMPOSITION

	757 INT	768 PTGS	760 PTGS	757 HASH	757 LASH	768 COAL	760 HASH	760 LASH
Sb	1	2	0.6	1	0.6	0.7	1	0.4
As	12	25	5	6	4	4	6	2
Br	1	0.6	1	2	2	1	3	2
Cs	1	7	2	4	2	1	0.6	0.3
Cl	47	22	27	48	42	36	24	22
Cr	184	110	84	52	95	19	23	10
Co	30	20	5	3	6	9	4	3
Cu	48	64	41	28	25	23	29	21
Hf	4	5	6	4	2	1	4	1
B	29	180	72	66	24	48	55	45
Pb	20	21	21	13	8	6	11	6
Li	78	71	29	38	14	23	15	6
Be	2	2	2	1	1	1	2	1
Mn	410	62	207	93	90	35	127	141
Mo	2	1	8	2	3	0.5	1	0.5
Ni	31	68	69	16	42	20	8	3
Nb	46	25	28	15	10	14	16	8
Rb	23	61	39	28	11	7	13	6
Sc	34	19	13	17	12	7	12	7
Se	1	1	1	1	1	1	1	1
Sr	76	179	201	61	43	182	265	419
Ta	0.6	0.8	1	0.5	0.2	0.2	0.4	0.2
Th	6	7	7	4	2	2	4	2
W	1.4	1.2	1.8	1	1.5	0.4	1.1	0.4
U	2.9	3.6	3.5	2.0	1.3	0.9	2.2	0.9
V	368	141	89	99	63	42	77	40
Zn	16	14	28	85	9	8	9	8
Ce	47	39	40	38	29	20	28	13
La	23	22	19	18	16	9	14	7
Sm	5	4	4	5	4	2	3	2

LEGEND FOR TABLE 4-A,B.

757 INT - INTRUSIONS FROM SECTION 757, MT. GRANGER.
768, 760 PTGS - PARTINGS FROM TANTALUS AND DIVISION MOUNTAIN.
757 HASH - HIGH ASH SAMPLES, ASH >50 %, MT. GRANGER.
757 LASH - LOW ASH SAMPLES, ASH < 50 %, MT. GRANGER.
768 COAL - LOW ASH, < 30 %, TANTALUS.
760 HASH - HIGH ASH SAMPLES, ASH > 30 %, DIVISION MOUNTAIN.
760 LASH - LOW ASH SAMPLES, ASH < 30 %, DIVISION MOUNTAIN.

DISCUSSION

The three deposits studied from the Whitehorse Trough show differences in composition and rank, with generally high vitrinite contents and moderate inertinite contents. The main variation in maceral composition is shown by the liptinite content, which is low (<5%) in the Carmacks coals, but has concentrations up to 13% in the Division Mountain section. Liptinite is absent from the Mt. Granger section, in part due to the high rank of the deposit. Mineral matter content varies significantly between and within deposits, which may present potential quality control problems for coal utilization.

The Mt. Granger samples are coked, and original rank and composition are not directly obtainable. In samples from the general area that do not show significant effects of heating, reflectance values ranging from 2% to 4% Ro_{max} have been reported (Hunt, 1989; Hart and Radloff, 1990). Furthermore, the presence of coarse grained mosaic textures suggest an original coal rank of medium to low volatile bituminous, (< 1.5 % Ro_{max}) at the time of intrusion (Goodarzi and Jerzykiewicz, 1989).

Rank and petrographic composition of coals at Division Mountain suggest little alteration by thermal events, although the strata have been reportedly intruded by the overlying Carmacks Volcanics (Carne, 1990; Bostock, 1936). Minor alteration is suggested by slight elevation of reflectance in shear / strain zones within seams, and by epigenetic mineralization and elemental concentrations within these zones.

The differences in composition and rank between the Tantalus and Tantalus Butte sections at Carmacks have been addressed by Hacquebard, 1970 and 1972. He established tentative correlations between the main seams across the Yukon River based on lithotype and microlithotype trends, and has attributed the drastic rank increase southward across the river to the proximity of Carmacks Volcanics; however, the study of coal rank from the additional trenches southward (which were not available at the time of Hacquebard's investigation) suggest that faulting and folding may have played a greater role in the rank elevation (in terms of variable burial depths).

The high rank and inertinite contents place the coals from Mt. Granger and Tantalus outside of the "idealized" reactive maceral and rank range for liquefaction processes (Davis, 1976); however the lower rank and higher liptinite concentrations at Division Mountain, and to a lesser extent, Tantalus Butte, have better liquefaction potential from a petrographic viewpoint. The Tantalus Formation contains good quality coking coals in the Tantalus area based on rank and petrographic data.

The elemental composition of the coal from each area is similar, and falls within normal coal averages. The Division Mountain section contains a few anomalously high Zn values, which may be attributable to epigenetic impregnation of fluids along fractures or shear zones. The Carmacks volcanics are reported to intrude the Tantalus Formation at this location, and may be a possible source. High concentrations of Ca in the Carmacks coals were likely introduced into fractures by groundwater action. Elements of environmental concern, for example S, Cl, B, U, Pb and Zn, occur in low concentrations in all sections. Variable ash content and rank could pose quality control difficulties and may necessitate washing prior to useage. As most elements are inorganically associated, washing may further reduce undesireable elements in the coal.

The intrusions at Mt. Granger are enriched in Fe, Mg, Ti, Cr, Co, Mn and V; Cr, Ni and Zn show a concentration in the coal compared to the other deposits, and may be derived from the intrusions relative to the other deposits.

Mineralogy correlates well with elemental composition. High Ti values correlate to the presence of anatase. Weddelite correlates with gypsum, and may be a product of low temperature ashing or natural weathering. Pyrite, jarosite and hematite are correlated with the Fe-rich Mt. Granger samples, however the latter two may be indicative of the weathered nature of the samples.

The coals from Division Mountain and Carmacks are acceptable for thermal utilization. The coals at Mt. Granger are less attractive because of their very high rank (due to intrusions) and ash contents. Additional exploration in the Mt. Granger area will be necessary to determine if the seams laterally have lower rank and ash contents.

The coals sampled at Mt. Granger have been coked and therefore are beyond optimal rank range for coalbed methane potential. However, potential does exist for other parts of the deposit if the seams were not intruded and are of a lower rank. The surficial geology of the deposit indicates that the seams are heavily faulted, and are at shallow depths; further exploration is needed to delineate coalbed methane potential in this area.

The Division Mountain area shows better methane potential than the Mt. Granger area. The surficial geology of the deposit suggests the steeply-dipping thick seam flattens out at greater depth, potentially causing rank elevations. The potential for deep-lying seams coupled with structural and hydrological gas trapping exists within the Nordenskiold River Valley. High liptinite contents of these coals may contribute to generation potential.

Tantalus Butte and Tantalus show significant rank variations over short distances, and frequent faulting and shearing make coalbed methane potential difficult to predict. The seams dip steeply, and depth and inclination in surrounding areas is not well known. Variable rank, seam quality, potentially beneficial hydrological conditions (seams below Yukon River ??) and geology suggest potential, but detailed exploration is needed in this small area.

The rank and petrographic composition of the Tantalus coals is very similar to the coals from the Elk Valley Coalfield as reported by Dawson and Clow (this volume). The Elk Valley coals have relatively good methane contents and absorption capacities; the Tantalus area coals may therefore have similar methane potential.

SUMMARY

Coal occurrences within the Whitehorse Trough show a wide range of rank and quality. Petrographic composition and rank suggest favourable conditions for coal utilization for the Division Mountain and Carmacks deposits. The intruded and moderately deformed Whitehorse deposit will have less utilization potential. Rank and compositional variations of the coals suggest the presence of good thermal and coking coals, and potential coalbed methane generation conditions scattered throughout the Whitehorse Trough. The geochemistry and mineralogy of the deposits indicates the concentrations of undesireable elements are low, and predominantly hosted in the mineral matter within the coal. In all deposits, detailed exploration will be needed to further determine the geological features, composition and resources of these deposits.

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AN OVERVIEW OF SOME SELECTED COAL RESOURCES OF THE WORLD

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ABSTRACT

Coal is a widely dispersed resource on our planet. Some nations are blessed with large deposits of mineable coal, the resources of other countries are meager, nevertheless numerous countries around the world report the presence of coal within their boundaries. The reported total coal output from 60 countries during 1990 was 4.7 billion metric tonnes. The production of the four largest coal producers alone contributed 66% to this total. This paper is a brief overview from the personal perspective of a consulting geologist. It covers coal in a number of developing countries in Africa and Asia where, regardless of the size and quality of the respective resource, coal plays an important role in the local economies.

INTRODUCTION

Coal is a widely dispersed resource on our planet and comprises a multitude of substances ranging from lignite to anthracite. Some nations are blessed with large deposits of mineable coal, the resources of other countries are meager, nevertheless numerous countries around the world report the presence of coal within their boundaries.

The estimated production of all ranks of coal from 60 countries around the world (Figure 1, Table 1) during 1990 stood at more than 4.7 billion metric tonnes (Mining Magazine, October 1991). Twenty-five countries reported coal output of at least 10 million tonnes (Mt), and collectively accounted for more than 98% of the total. With a production of 1 053 Mt, China was the largest producer. The next three most productive countries were U.S.A. (927 Mt), U.S.S.R. (703 Mt) and Germany (427 Mt). Together these four top producers contributed more than 66% to the world's total coal production. Canada, with its production of 68.3 Mt, ranks 12th on the list of the producers.

Even the most basic research will discover a number papers and publications concerned with coal situation in the "major league" coal producing countries. The present paper, therefore, will not contribute to this growing list; instead, it is intended to be a brief review of the coal situations in some of the lesser reported

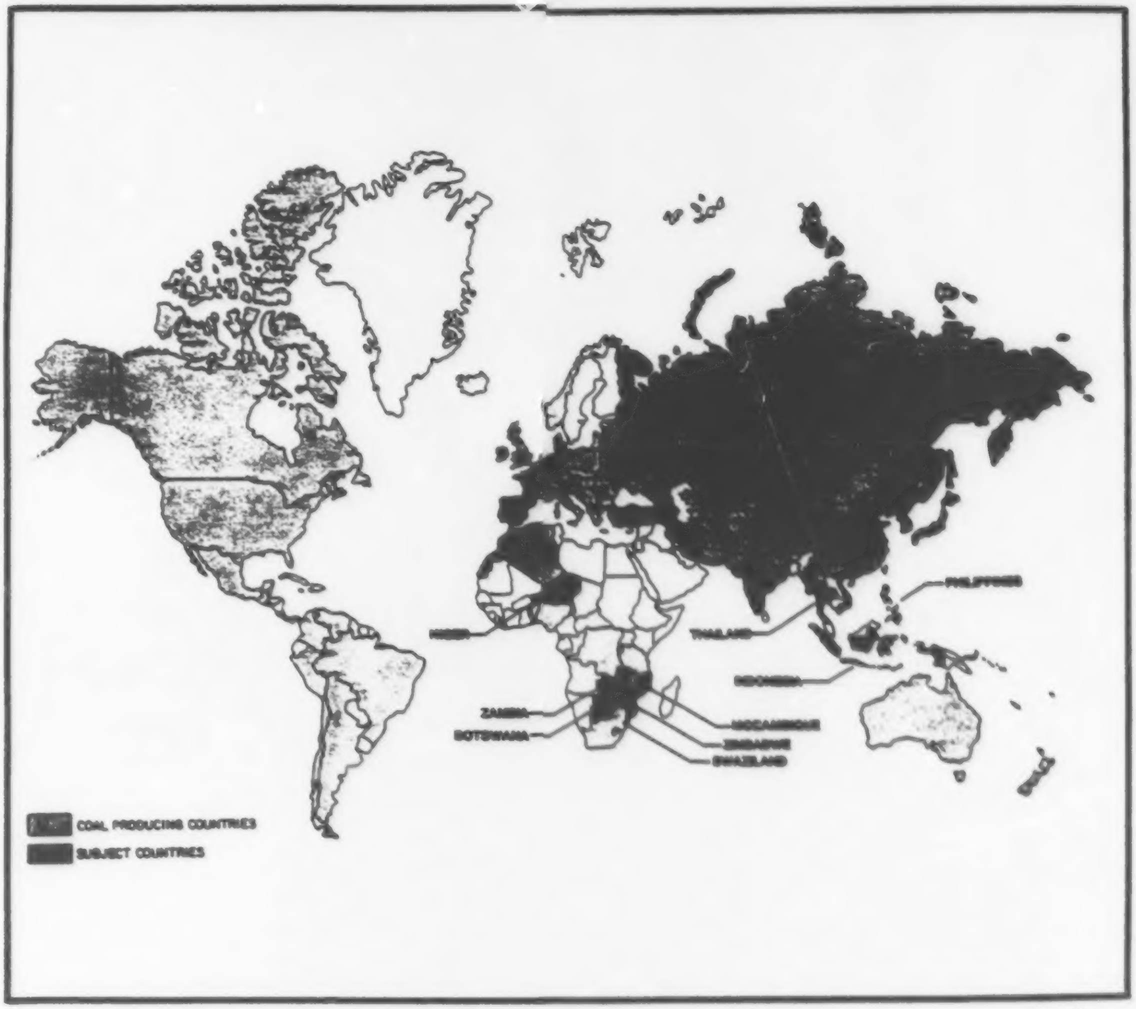
PHILIPPINES
NIGER
THAILAND
INDONESIA
ZAMBIA
BOTSWANA
MOZAMBIQUE
ZIMBABWE
SWAZILAND
COAL PRODUCING COUNTRIES
SUBJECT COUNTRIES

Figure 1. Coal producing countries of the world

Table 1: World Coal Production 1990
(million metric tonnes)

	All Ranks	Hard Coal	Lignite Brown Coal	% of Total
1 China	1 053.000	967.000	86.000	22.3848
2 U.S.A.	927.000	629.000	298.000	19.7063
3 U.S.S.R.	703.000	545.000	158.000	14.9445
4 Germany	427.000	70.000	357.000	9.0772
5 Poland	216.000	148.000	68.000	4.5918
6 Australia	210.200	162.500	47.700	4.4685
7 India	210.000	201.500	8.500	4.4642
8 S. Africa	206.000	206.000		4.3792
9 Czechoslovakia	107.000	22.000	85.000	2.2746
10 U.K.	95.000	95.000		2.0195
11 Yugoslavia	76.000	0.350	75.650	1.6156
12 Canada	68.300	58.900	9.400	1.4519
13 Greece	50.000		50.000	1.0629
14 North Korea	48.500	48.500		1.0310
15 Turkey	45.500	3.500	42.000	0.9672
16 Romania	38.200	5.200	33.000	0.8121
17 Spain	36.000	19.600	16.400	0.7653
18 Bulgaria	30.200	0.200	30.000	0.6420
19 Colombia	19.000	19.000		0.4039
20 Hungary	17.600	1.700	15.900	0.3741
21 South Korea	17.200	17.200		0.3656
22 France	12.800	10.500	2.300	0.2721
23 Thailand	12.400		12.400	0.2636
24 Indonesia	10.600	10.600		0.2253
25 Mexico*	10.000	10.000		0.2126
26 Japan	8.300	8.300		0.1764
27 Mongolia	7.700	0.200	7.500	0.1637
28 Brazil	6.500	6.500		0.1382
29 Zimbabwe	5.000	5.000		0.1063
30 Vietnam	4.500	4.500		0.0957
31 Pakistan	3.000	3.000		0.0638
32 Chile	2.700	2.700		0.0574
33 New Zealand	2.600	2.400	0.200	0.0553
34 Venzuela	2.500	2.500		0.0531
35 Austria	2.400		2.400	0.0510
36 Albania	2.000	2.000		0.0425
37 Iran	1.600	1.600	1.500	0.0340
38 Italy	1.560	0.060	1.500	0.0332
39 Belgium	1.440	1.440		0.0306
40 Philippines	1.200	1.200		0.0255
41 Botswana	0.660	0.660		0.0140
42 Morocco	0.530	0.530		0.0113
43 Argentina	0.520	0.520		0.0111
44 Taiwan	0.520	0.520		0.0111
45 Norway	0.500	0.500		0.0106
46 Zambia	0.340	0.340		0.0072
47 Portugal	0.280	0.280		0.0060
48 Afghanistan*	0.200	0.200		0.0043
49 Niger	0.160	0.160		0.0034
50 Swaziland	0.153	0.153		0.0033
51 Nigeria*	0.150	0.150		0.0032
52 Egypt	0.125	0.125		0.0027
53 Tanzania	0.100	0.100		0.0021
53 Peru	0.100	0.100		0.0021
54 Zaire	0.100	0.100		0.0021
55 Burma	0.042		0.042	0.0009
57 Mozambique	0.040	0.040		0.0009
58 Malawi	0.030	0.030		0.0006
59 Ireland	0.025	0.025		0.0005
60 Algeria	0.010	0.010		0.0002
TOTAL	4 704.085	3 297.193	1 406.892	

* Estimated

Source: Mining Magazine, Oct. 1991

countries in the developing world, where demographics and high economic imperatives may transform the energy 'maps' within a few decades. This overview reflects the perspective of a consulting geologist who has been privileged to observe and participate in some of these continuing changes. Regardless of the size of the particular resource or reserves, production level or quality parameters, coal has a very important role in the economics of these countries.

NIGER

Niger is a large, landlocked and thinly populated, country in northwestern Africa. Its area totals around 1.3 million km^2 and the population is estimated to be in excess of 6 million. Most of Niger is Sahara desert or Sahel, resulting in a heavy concentration of population along the course of the Niger River in the extreme southwestern part of the country. Being considered as one of the world's least developed countries, Niger is anxious to develop local energy resources to spur its economic development. In addition, as is the case elsewhere in Africa and throughout the Sahel in particular, its sparse vegetation cover is being rapidly depleted through the use of fuel wood in domestic use. Therefore Niger desperately needs new energy sources for everyday use by its growing population.

Coal could be part of a possible partial solution to Niger's needs, except for the fact that the presently proven and partially developed resource occurs in the central part of the country north of Agadez, more than a thousand kilometres from the populated corridor along the Niger River. Therefore the Government of Niger, with international assistance, is continuing its efforts to discover mineable coal nearer to Niamey.

The best known coal deposit is at Sonichar, approximately 1 000 km northeast of the capital Niamey. The coal measures are of Carboniferous age and are part of early sedimentation in the Iullemeden basin, a major basin occupying the western half of Niger. The coal seams approach the surface in an area where the Iullemeden sediments come in contact with the crystalline l'Air massif to the east. The coal was discovered during the course of exploration for uranium along the l'Air, and in 1981 a small open pit coal mine was developed to provide fuel for a 32 MW thermal plant that generates electricity for uranium mines at Arlit, some 200 km to the north. The Sonichar mine operates at an annual production rate of 160 000 tonnes.

A number of coal seams are known to be present at Sonichar, but only two are economic, varying in thickness between 1 m and 8 m. The deposit has a lensoid shape, and the total reserves at Sonichar have been estimated at approximately 9 Mt, of which less than 4 Mt are proven. The coal has high ash contents, up to 60%. The two seams are blended to produce a power plant feed with the following characteristics:

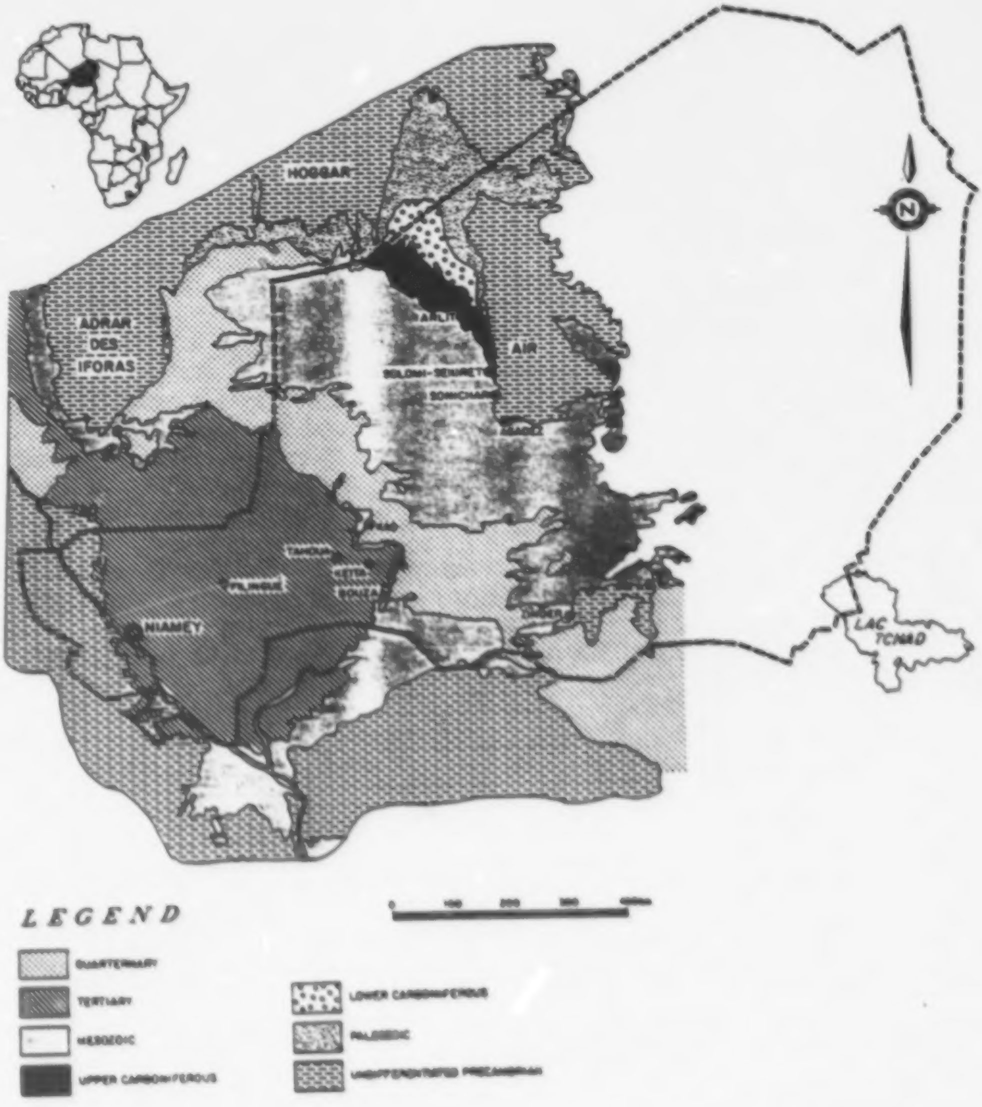
HOGGAR
ADRAR DES IFORAS
AIR
ARLIT
TAHOUA
KETA
BOUZA
FILINGUE
NIAMEY
LAC TCHAD
N
0 100 200 300 400km
LEGEND
QUARTERNARY
TERTIARY
MESOZOIC
UPPER CARBONIFEROUS
LOWER CARBONIFEROUS
PALEOZOIC
UNDIFFERENTIATED PRECAMBRIAN

Figure 2. General geology of the Iullemeden Basin, Republic of Niger

Moisture	3%
Ash	49%
Volatile Matter	17%
Fixed Carbon	31%
Sulphur	0.5%
Calorific Value	3 760 kcal/kg
HGI	60-70

Elsewhere in Niger coal occurrences have been reported from water wells dug in younger sediments filling the central portions of the Iullemeden basin in the general Filingue-Tahoua-Bouza area. These occurrences are being investigated, but as yet the efforts to discover economically viable coal deposits have not been successful.

BOTSWANA

Botswana is an arid, landlocked country in southern Africa. It covers approximately 582 000 km^2 and has a population around 1.2 million. With few exceptions the population resides within a narrow corridor along the Limpopo River valley paralleling Botswana's southeastern border with South Africa. Most of central Botswana is the Kalahari Desert, and the swamps of the Okavango Delta occupy much of the northwestern part of the country.

The coal resource of Botswana is vast, and with export potential in mind, in the past has been explored by a number of international companies. Due to the global softening of energy prices the interest in Botswana's coal has declined and most of the coal leases have been permitted to lapse.

Virtually all of Botswana's mineable coal would have to be mined underground. The only coal mine in the country, the Morupule Colliery, is a room and pillar operation served by an incline. Mining at Morupule commenced in 1973 at an annual rate of 40 000 tonnes. The production has steadily increased and today the colliery outputs around 650 000 tonnes per annum. Approximately 71% of the production is consumed by the nearby Morupule Power Plant, 28% is utilized by a Cu-Ni mine at Selebi-Phikwe, and less than 1% of the production is sold to other users.

The coal measures of Botswana are of Permian age and occur near the base of the Karoo supergroup, which has a wide distribution throughout southern Africa. The potentially mineable resource occurs within the basal subcrop areas of the Karoo supergroup along the eastern fringe of the Kalahari Desert. Frequent faulting divides the deposits into individual resource blocks. The structural dips within the fault blocks usually are within limits acceptable to underground mining.

At Morupule there are three coal seams of commercial significance but only the lowest in the sequence, the Morupule Main seam, is being mined. The seam is very consistent and averages about 9 m in thickness. Dips of the strata rarely exceed 2 degrees. The run-of-mine coal quality is given as:

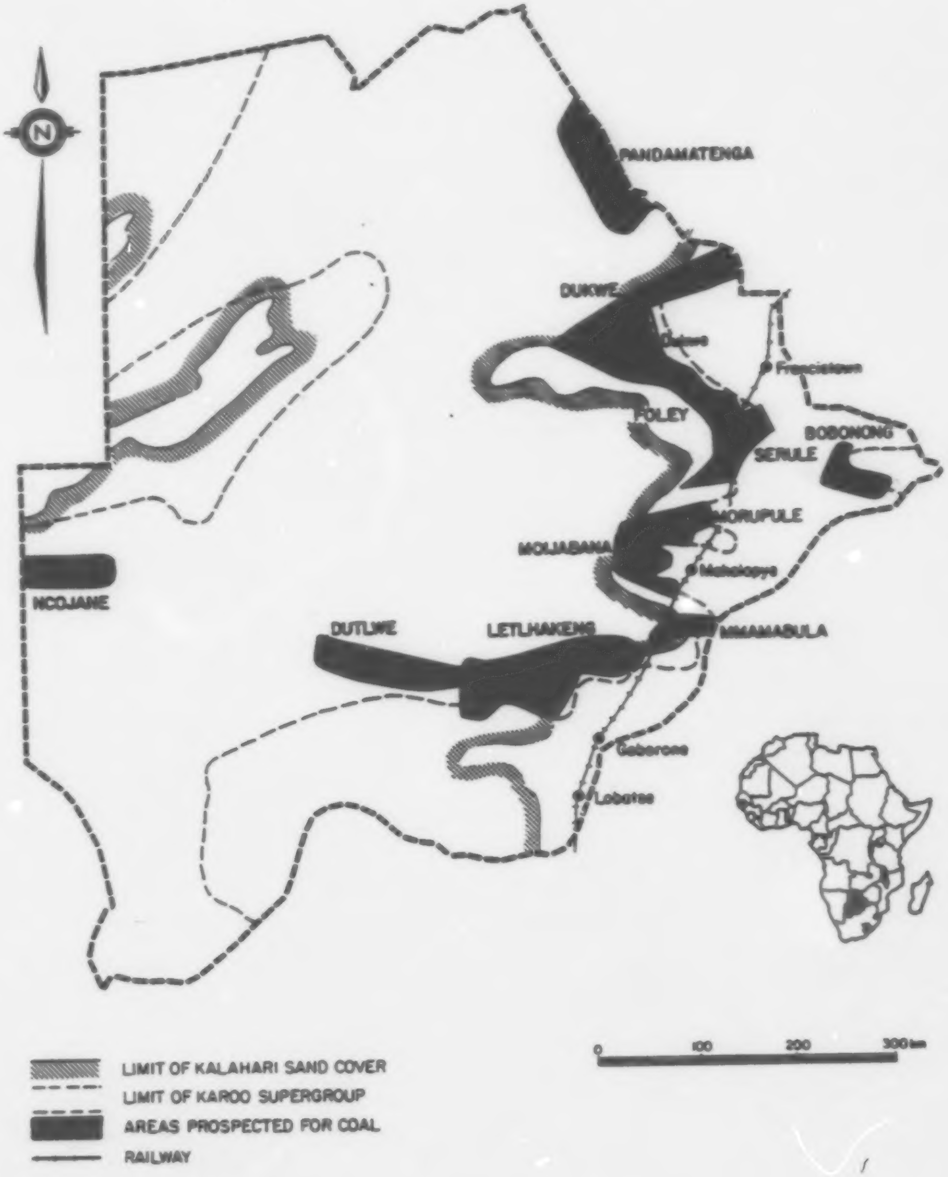
N
PANDAMATENGA
DUKWE
Francistown
FOLEY
BOBONONG
SERULE
MORUPULE
MOIJABANA
Mahalapye
NCOJANE
DUTLWE
LETLHAKENG
MMAMABULA
Gaborone
Lobatse
0
100
200
300 km
LIMIT OF KALAHARI SAND COVER
LIMIT OF KAROO SUPERGROUP
AREAS PROSPECTED FOR COAL
RAILWAY

Figure 3. Republic of Botswana

Moisture	5%	(As received basis)
Ash	19%	(As received basis)
Volatile Matter	22%	(As received basis)
Sulphur	2.5% max.	(Air dried basis)
Calorific Value	5 280 kcal/kg	(Dry basis)
HGI	55-70	

The reserves at Morupule are 95 Mt, with 40 Mt being classified as proven.

The estimated insitu coal resource of the three best prospected resource blocks, Morupule-Moijabana, Mmambula and Letlhakeng, which together comprise less than half of the prospected extent of the Karoo subcrop, amount to 17 640 Mt. The quality of the coal in these resource blocks generally is comparable to that of the coal at the Morupule Colliery.

SWAZILAND

The Kingdom of Swaziland is a small country in southeastern Africa, bordered by Mozambique to the east and surrounded by South Africa everywhere else. It has an area of less than 17 400 km^2 and a population around 700 000. Swaziland also has a large coal resource that is relatively little exploited at the present time.

The coal measures in Swaziland are part of a narrow band (average widths 15 km) of sediments belonging to the Karoo supergroup that traverse the country in north-south direction for a distance of 150 km. The strata have an average dip of 7 degrees east/southeast. Two coal zones are present, but most seams with mineable thickness are in the lower zone. A seam known as the Main Seam is continuous at mineable thickness throughout the entire coal field. Coal seams in the upper zone are usually thin and of poor quality. The coal seams occur within large volcanic structures, and volcanism has caused extensive regional faulting, fracturing and igneous intrusions. As a result high volatile bituminous coal has been converted to semi-anthracite, with volatile matter ranging from 6% to 12% and an absolute maximum 14% to 15%. In some instances the coal seams have been replaced by dolerite. The faults and intrusions cause difficult mining conditions.

The total insitu coal resource of the two coal zones has been estimated at 1 017 Mt. Of this total, 567 Mt have been classified as "established" by the Swaziland Geological Survey and Mines Department. The established resource is further divided between the lower and upper coal zones at 485 Mt and 82 Mt, respectively.

The only coal producer in the country is the Mpaka Colliery, a semi-mechanized underground room and pillar operation. Two years ago the colliery was producing approximately 200 000 tonnes annually, but since then the output has declined to around 160 000 tonnes. The coal output fluctuates with the market demand for Mpaka's coal. Being semi-anthracite, only 15% of Mpaka's saleable output is being sold locally; most of the coal is being exported to its only foreign customer--a cement works in Kenya.

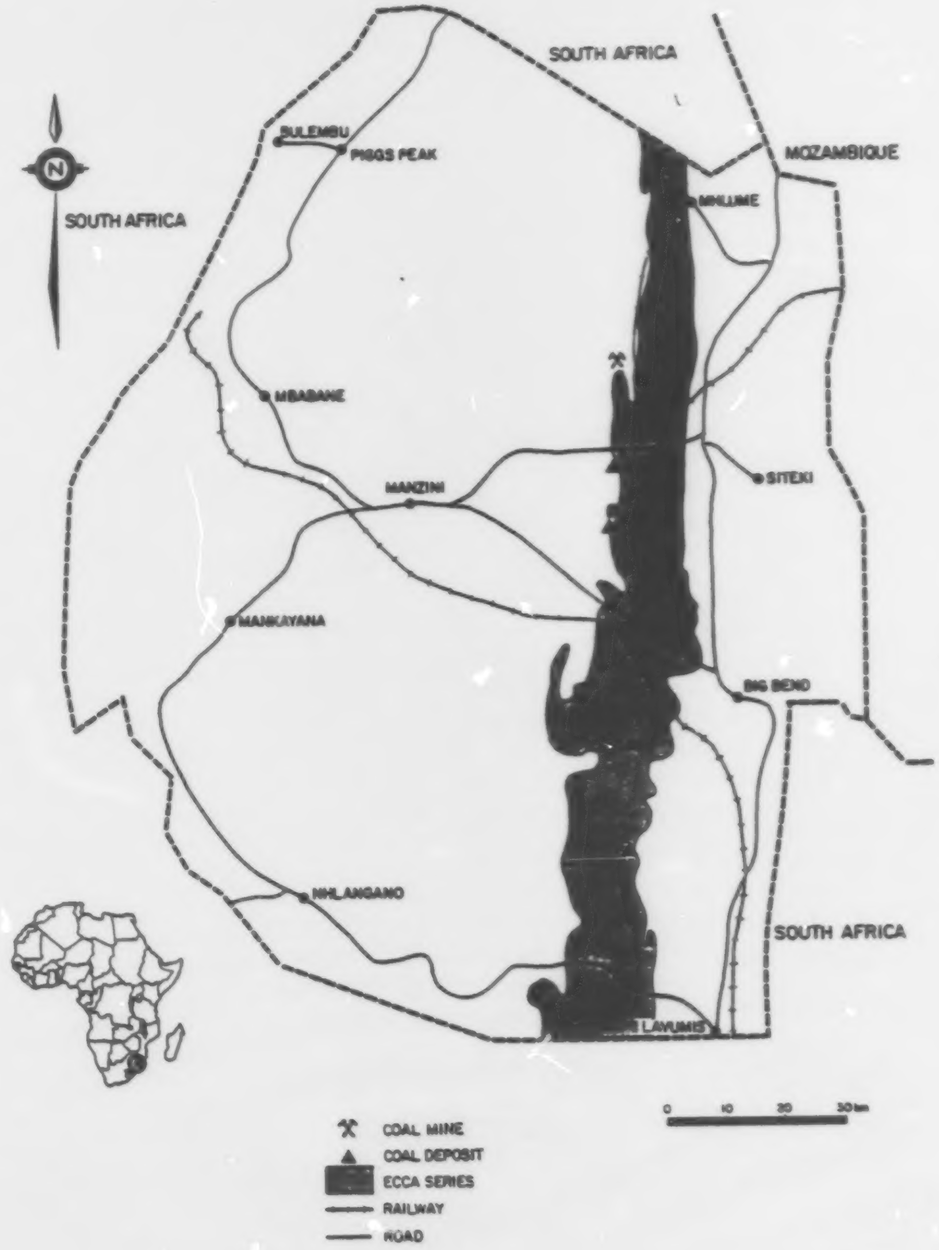
SOUTH AFRICA
MOZAMBIQUE
N
BULEMBU
PIGGS PEAK
SOUTH AFRICA
MHLUME
MBABANE
MANZINI
SITEKI
MANKAYANA
BIG BEND
NHLANGANO
SOUTH AFRICA
LAVUMISA
0 10 20 30 km
COAL MINE
COAL DEPOSIT
ECCA SERIES
RAILWAY
ROAD

Figure 4. The Kingdom of Swaziland

The mineable reserves at Mpaka are in the order of 9.8 Mt. The quality parameters are:

Moisture	1.3%
Ash	14.1%
Volatile Matter	12.7%
Fixed Carbon	72.0%
Sulphur	0.3%
Calorific Value	6 930 kcal/kg

It is interesting to note that Swaziland's coal exports are offset almost equally by coal imports, because the local coal consuming industries are not equipped to use semi-anthracite and prefer to import lower rank coal from South Africa. The consumption of the net supply of coal in Swaziland breaks down as follows: industrial users 59%, households and other users 22% and Swaziland Railway 19%.

ZAMBIA

Zambia, another landlocked nation in southern Africa, has a territory comprising 752 614 km^2 and a population around 7 million. Zambia is a country endowed with rich mineral resources. Zambian Copper Belt is a term familiar to most students of geology. Not as well known is the fact that Zambia has a large coal resource, the true extent of which as yet is not fully known.

Rocks of the Permian Karoo system in Zambia occur over a large area in the western part of the country and in several elongated, fault-defined, depositional basins in southeastern and eastern Zambia. Except for the developed coal deposits in mid-Zambezi Valley in the southeastern part of the country, coal elsewhere is found in remote areas and is almost unexplored. Therefore it is difficult to estimate Zambia's inventory of potentially mineable coal. It is certain, though, that the ultimate resource is very large.

The mid-Zambezi coal deposits are within a block of downfaulted Karoo sediments and are bounded by complex fault systems. Zambia's only coal mine, Maamba Colliery, is situated in the mid-Zambezi Siankondobo coalfield. The coalfield comprises two sub-basins, Kanzinze and Izuma, and has total coal reserves in the order of 87.25 Mt, of which 69.25 Mt are classified as proven.

The coal measures at Maamba contain frequent vitrinitic coal bands, but only one seam, known as the Main Seam, contributes to coal reserves. The Main Seam varies in thickness between 2 m and 10 m. The coals in Zambia in general have high ash contents, and at Maamba ash content is one of the parameters that defines mineable reserves: coal with ash greater than 25% is not considered as mineable. Maamba's run-of-mine (ROM) coal quality parameters are:

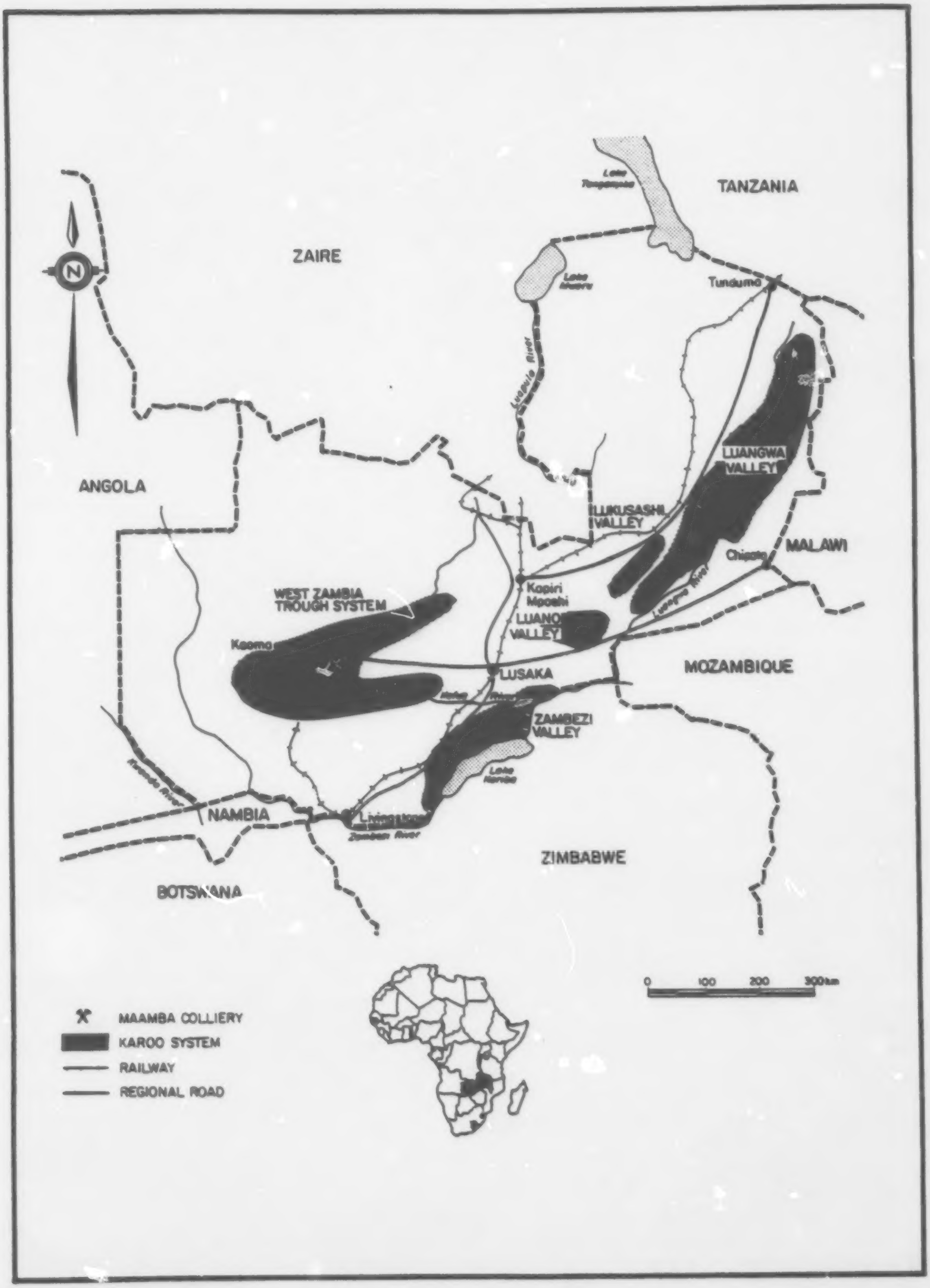
TANZANIA
Lake Tanganyika
ZAIRE
N
Lake Mweru
Tunduma
Luapula River
LUANGWA VALLEY
ANGOLA
LUKUSASHI VALLEY
MALAWI
Chipata
Kapiri Mposhi
WEST ZAMBIA TROUGH SYSTEM
LUANO VALLEY
Luangwa River
Kaoma
LUSAKA
MOZAMBIQUE
Kafue River
ZAMBEZI VALLEY
Lake Kariba
Kwando River
NAMBIA
Livingstone
Zambezi River
ZIMBABWE
BOTSWANA
0
100
200
300km
MAAMBA COLLIERY
KAROO SYSTEM
RAILWAY
REGIONAL ROAD

Figure 5. Republic of Zambia

Moisture	1.0%
Ash	25 %
Volatile Matter	17 %
Fixed Carbon	57 %
Sulphur	2.5%
Calorific Value	5 600 kcal/kg

Mining of coal in the Maamba area commenced in 1966, and the Maamba Colliery has been in continuous operation since 1969. It is an open pit, and mining is a combination of truck-shovel and dragline operation. During 1985-86 the mine underwent rehabilitation and reorganization to upgrade its annual production capacity to more than 1 Mt. During the past decade Maamba's annual output has varied between 700 000 and 900 000 tonnes of coal. Recent information (Mining Magazine, October 1991), however, suggests that during 1990 the output had fallen to 340 000 tonnes.

Most of Maamba's coal is consumed domestically and approximately 8% of its production (at the higher production levels) is exported in Tanzania, Malawi and Zaire. The exports are offset by imports of metallurgical coal amounting to 10% of Zambia's annual coal consumption. The principal users of domestic coal are copper mines, chemical plants producing fertilizers and cement works, which jointly consume 74% of Zambia's coal output. Other large users of domestic coal are sugar refineries and breweries.

ZIMBABWE

Zimbabwe, a landlocked state in southern Africa, has an area of 390 759 km^2 and its population is crowding the 9 million mark. It has a significant coal mining industry, with a long history. In fact, with its present annual coal production at a steady 5 Mt, Zimbabwe is a major coal producer on the African continent, second only to South Africa.

Coal measures in Zimbabwe are part of the Karoo supergroup. The total resource is very large, and is found in a number of Karoo depositional basins. The total coal resource in the principal depositional basins is estimated at 5 176 Mt, of which 215 Mt are classified as proven and a further 2 500 Mt are described as probable. If hypothetical and speculative categories, as well as lesser known coalfields and areas are taken into consideration, the potential coal resource of Zimbabwe would most likely double. Presently the largest and best known deposits are in the mid-Zambezi Valley in the northwestern part of the country. The Zambezi Valley deposits comprise 87% of Zimbabwe's known coal resource.

The best developed coal reserves are in the Hwange area in the extreme northwestern part of Zimbabwe. The potential of the Hwange area coalfields alone approaches 2 000 Mt. At Hwange the coal measures have been preserved between two major faults--the Entuba fault uplifting granites to the south and the Deka downfaulting late Karoo basalts to the north.

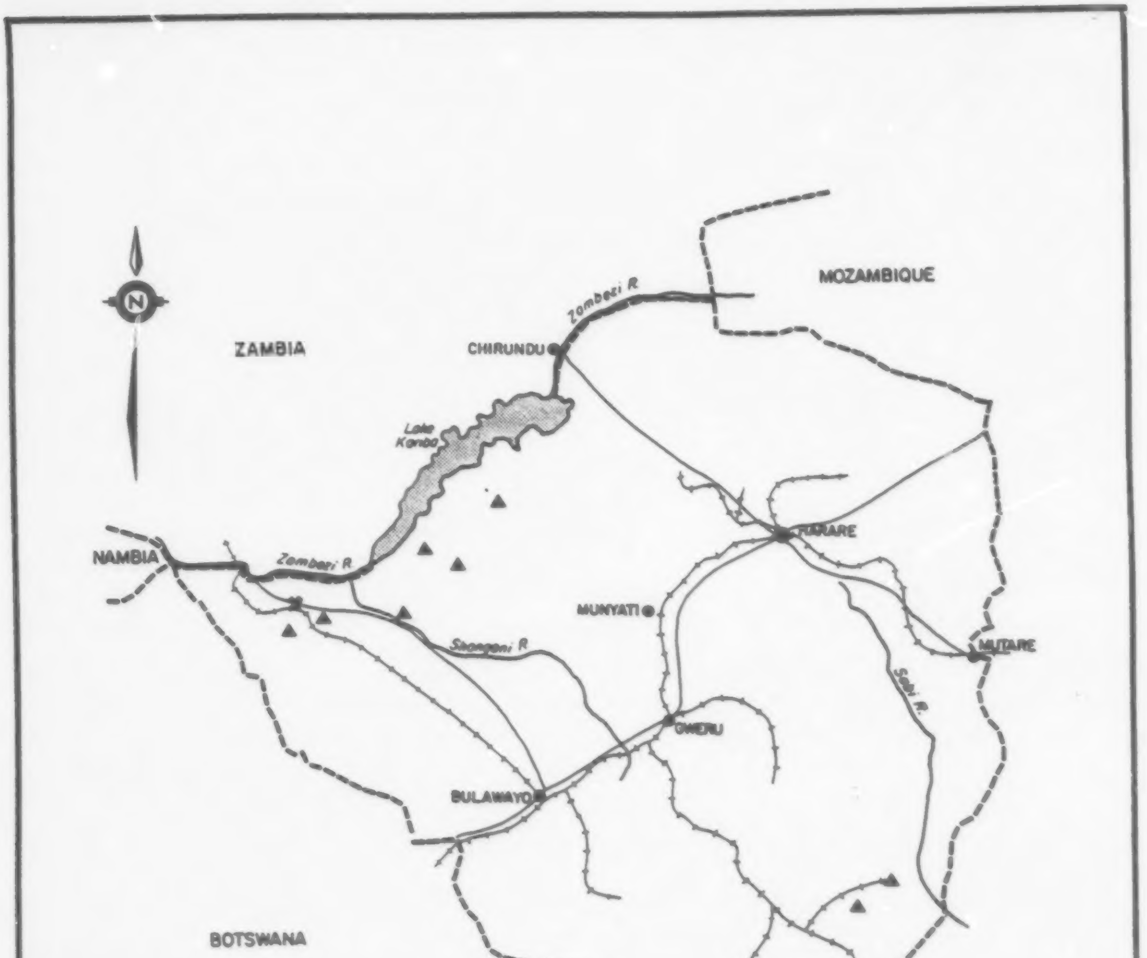
N
ZAMBIA
MOZAMBIQUE
Zambezi R
CHIRUNDU
Lake Kariba
NAMBIA
Zambezi R
HARARE
MUNYATI
MUTARE
Shangani R
Sabi R.
GWERU
BULAWAYO
BOTSWANA
Limpopo R
SOUTH AFRICA
0
100
200
300 km
▲ COAL DEPOSITS/AREAS
⚒ WANKIE COLLIERY
RAILWAY
REGIONAL ROAD

Figure 6. Republic of Zimbabwe

Zimbabwe's only coal mine, Wankie Colliery, is also in the Hwange area. The first mining shafts in the area were sunk around the turn of the century. With interruptions, mining at Wankie has continued to this day. For many decades mining was entirely underground, but today 85% of Wankie's 5 Mt annual production comes from open pit. The first open pit was opened in 1970 and over past twenty years the demand for coal in the country has been responsible for a spectacular growth in production at Wankie. The underground operations are room and pillar, and surface mining is a combination dragline/truck and shovel operation.

One seam, the Wankie Main, is being mined. It varies in thickness between 3 m and 13 m, and has stratigraphically variable quality. The lower part of the seam, 0 to 6 m, is vitrinitic, bright banded coal with good coking characteristics. The upper 3 m to 10 m are durain-rich coal. The lower part of the seam has ash content in the range of 8% to 14% and volatile matter 25% to 30%. The ash content of the upper portion varies between 14% and 24%, and the volatiles average 18%. The upper part of the Wankie Main seam is used as thermal coal. The underground workings remove only the bottom slice of the seam.

Most of Wankie's coal is consumed by electric power generating plants in Zimbabwe. The Hwange Power Station alone consumes nearly 50% of Wankie's production; other thermal plants using coal are in Harare, Bulawayo and Munyati. Smaller amounts of coal are consumed by other domestic users, including some who gasify coal to provide process heat. About 1.5% of the output is exported to Zaire, Botswana, Zambia, Malawi and Mozambique.

All of Wankie's coal is released from the same seam in the same coalfield, and the ROM coal must satisfy a variety of markets with requirements for product coal with widely differing physical and chemical characteristics. These requirements are met through selective mining, and by crushing, screening and washing of the ROM coal.

MOZAMBIQUE

Mozambique is a southern Africa country situated on the coast of the Indian Ocean. Its territory comprises 799 380 km^2 and the population numbers around 15 million. Mozambique is a country rich in mineral resources, including a large coal resource. It is also a sad example of what guerrillas and warfare can do to a thriving coal mining industry.

Coal deposits in Mozambique are known to occur in at least five different areas dispersed throughout the country. The best known deposits, with a history of mining, are situated along the Zambezi River Valley in Tete Province, in northwestern Mozambique. Because the Tete coal resource is very large and already has been developed to some degree, to date little interest has been shown in the other coal areas of the country.

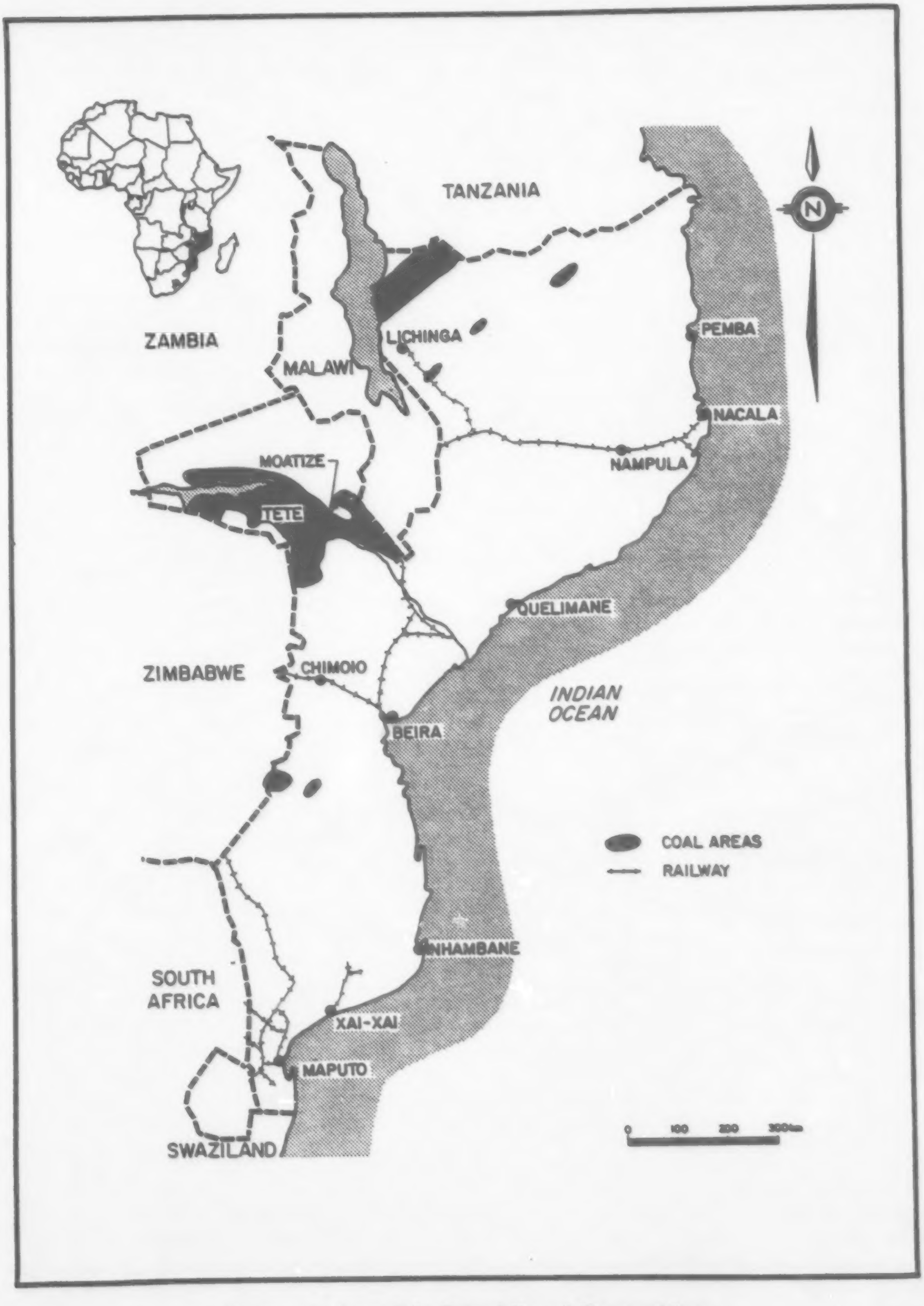
TANZANIA
ZAMBIA
MALAWI
LICHINGA
PEMBA
NACALA
NAMPULA
MOATIZE
TETE
QUELIMANE
ZIMBABWE
CHIMOIO
BEIRA
INDIAN
OCEAN
COAL AREAS
RAILWAY
NHAMBANE
SOUTH
AFRICA
XAI-XAI
MAPUTO
SWAZILAND
N
0
100
200
300km

Figure 7. People's Republic of Mozambique

Coal in Tete Province is found in four separate resource areas. Tete's insitu coal resource, in seams considered as mineable, has been estimated at 9 530 Mt, of which 938 Mt are classified as measured. In fact, the resource is so large that a sizeable area underlain by good quality coal has been flooded by the Cahora Bassa reservoir formed behind a recently constructed hydroelectric dam on the Zambezi River northwest of the Town of Tete. Mining of coal has taken place in the Moatize Basin east of Tete, where the estimated insitu resource is 1 968 Mt and the measured reserves are 87 Mt.

Systematic mining of coal at Moatize was started in 1920, and by 1975 the annual production had reached nearly 600 000 tonnes. All mining has been underground using the room and pillar method. In total, there are, or have been, eight separate operations, Chipanga I to VIII. Both metallurgical and thermal coal was being produced and shipped via a 600 km rail line to the port of Beira, en route to markets in Europe, Japan and India. Guerrillas destroyed the railway in 1982, and since then mining at Moatize has come to virtual halt. During 1981, the last year of full production, the output was 534 500 tonnes. This contrasts dramatically with the 40 000 tonnes of coal that were mined in 1990 and sold as steam coal to sugar refineries and cement plants locally and to customers in neighbouring Malawi.

Tete coal measures are part of the Permian Karoo supergroup. The Moatize Basin is a graben-like structure that has been downfaulted in an igneous basement complex. The basin is badly faulted and the coal measures now occur in numerous small blocks. A statistical study of faulting at Moatize has predicted the possibility that a fault with a 10 m vertical displacement will occur every 50 m. The structure has been complicated further through the intrusion of numerous dolerite dikes. These dikes are on the average 15 m thick and their thermal effects extend into the coal to distances 2-3 times the width of the particular dike. The strata dip at 13 to 17 degrees NE or SE, depending on the position within the basin.

A number of coal seams are present in slightly more than 300 m of the lower Karoo strata, but only one seam, the Chipanga, is being mined. The seam averages 32 m in thickness, however coal is being extracted from the bottom 4 m only as the ash content increases upwards. The ROM product is metallurgical grade coal that was being marketed without beneficiation other than hand picking.

For nearly a decade now the Government of the Peoples' Republic of Mozambique has been working on plans for a multi-year, two-phase expansion of coal mining operations at Moatize, as well as a total rebuilding of the railway to the coast and a major port expansion at Beira. Phase 1 called for the rehabilitation of five underground mines to raise their combined annual output to 1 million tonnes. Phase 2 would see large investments by international partners in open pit mines that would produce as much as 25 Mt of ROM coal annually. It will be interesting to see what effect the recent changes in Eastern Europe and the Soviet Union will ultimately have on these plans, as Phase 1 was to be carried out with the assistance of the U.S.S.R. and the former East Germany.

THAILAND

Thailand is one of the Southeast Asia economic "tigers" with a booming economy, an energetic population in excess of 50 million, a land area of 514 000 km^2, and an ever growing need for energy.

Coal in Thailand occurs in Tertiary or lower Pliocene basins. Seventy-six such basins have been identified in the country, and 40 are known to have workable coal deposits or identified coal occurrences. The coal usually is confined to smaller sub-basins within a larger basin. The coal bearing strata belong to sediments that have their origins in non-marine or brackish water marine environments. The thicknesses of mineable coal seams vary between the deposits, but some seams are known to be up to 40 m thick. The coal measures commonly have been affected by gravity faulting.

Thailand's total coal resource has been estimated at 2 350 Mt. Of this total, 1 270 Mt are classified as measured reserves. Nearly 65%, or 821 Mt, of the measured total are in one deposit at Mae Moh in northeastern Thailand. The Mae Moh deposit also has some 670 Mt in the indicated category. The next largest deposit is the recently discovered Saba Yoi in southern Thailand. As yet no measured reserves are available for this deposit; exploration is continuing and the currently indicated reserves are in the order of 150 Mt, with the ultimate potential estimated as high as 1 500 Mt. The other known Thai coal deposits are much smaller; for example, the currently mined deposit at Krabi in southern Thailand has 83.6 Mt measured and 120.8 Mt indicated reserves.

The Mae Moh deposit occurs in a small, faulted synclinal basin. Two principal coal seams are present, both in the order of 10 m to 37 m thickness. At Krabi the reserves are in one seam that ranges in thickness from 0 m to 25 m. There appear to be one principal seam at Saba yoi with the known thickness ranging between 10 m and 34 m.

The proven coal reserves in Thailand are mainly in northeastern part of the country, with some found in the south. These are mainly deposits of lignitic coal. Minor deposits of subbituminous coal are also found throughout Thailand. The lignites are characterized by high ash and sulphur contents. The heat content of the lignite at Mae Moh is around 2 400 kcal/kg, the Krabi lignite has a heat value of only 1 900 kcal/kg, and reports place the Saba Yoi coal in the 3 000 kcal/kg range.

The coal production in Thailand has seen a tremendous growth. During 1977 the total production was only 0.44 Mt, and it had grown to 12.4 Mt in 1990. All coal is mined from the surface using truck and shovel mining methods. The largest mine is at Mae Moh which has an annual output around 6 Mt. The balance of the Thai production comes from a number of much smaller mines.

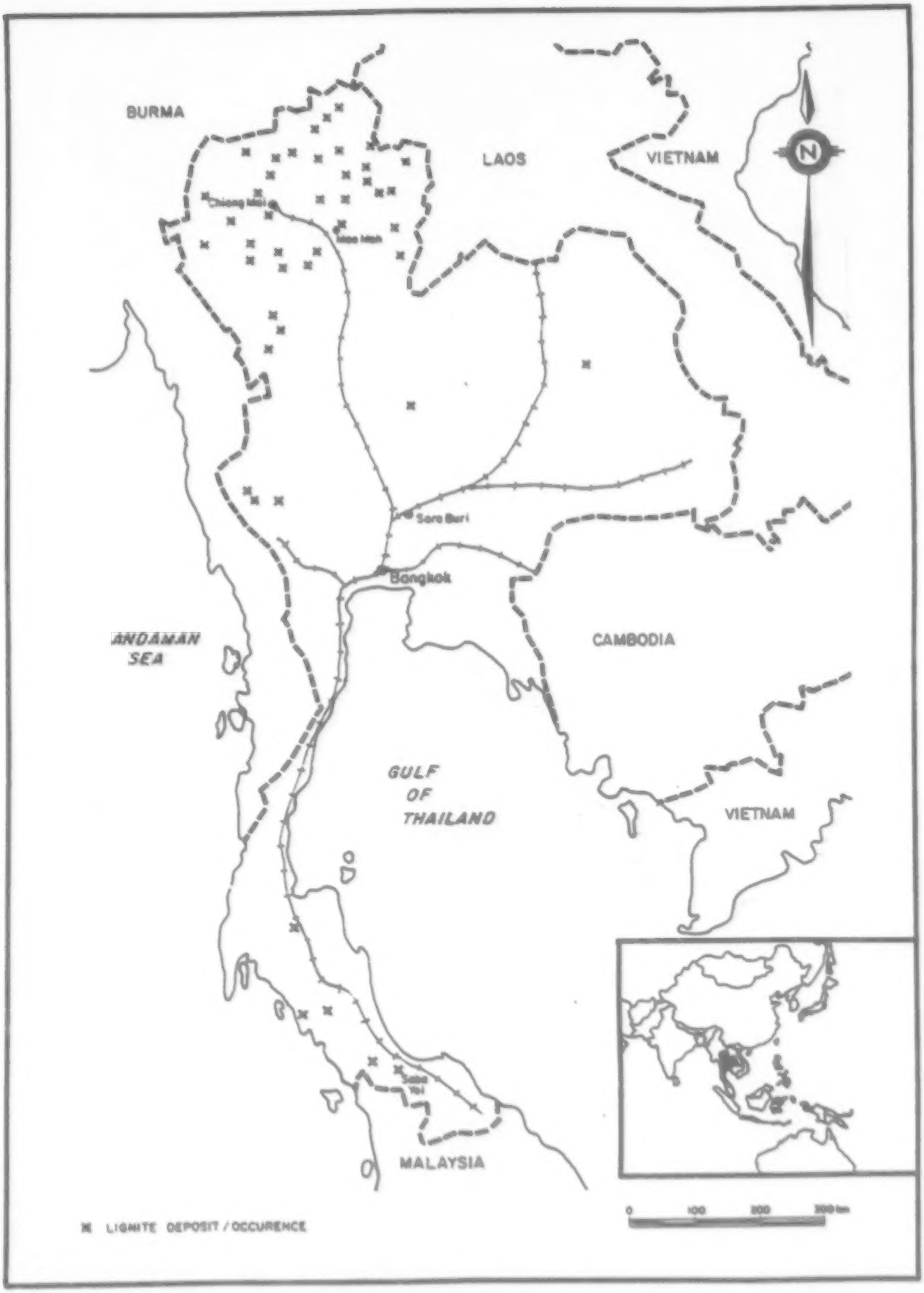
BURMA
LAOS
VIETNAM
N
Chiang Mai
Mae Moh
Sara Buri
Bangkok
ANDAMAN SEA
CAMBODIA
GULF OF THAILAND
VIETNAM
Saba Yoi
MALAYSIA
✖ LIGNITE DEPOSIT / OCCURENCE
0
100
200
300 km

Figure 8. Lignite occurences in Thailand

The development of coal deposits has a very high priority in Thailand. The largest consumer of coal is the electric power generating sector, which over the past decade grew by an average 10.7% annually; during the past few years the growth has been around 15% and has been forecast to continue growing at this rate. Presently the power sector consumes between 9 and 10 Mt annually. The next largest use of coal is in the manufacture of cement, consuming around 1.5 Mt in 1990.

The annual demand for coal is expected to reach 35 Mt by the year 2000. Forecasts show that domestic production of coal should be able to provide approximately 26 Mt of this demand, and therefore Thailand is actively striving to cultivate secure imports form other coal producing countries in Asia.

INDONESIA

Indonesia is a developing Southeast Asian country that spreads across 14 000 islands with a total area of about 2 million km^2. With a population of around 180 million, Indonesia is one of the world's most populous countries. Indonesia has a diversified natural resource base that includes significant coal deposits.

Coal in Indonesia is found on every major island, but the principal known deposits are on Sumatra and Kalimantan. Elsewhere the deposits are either small or are as yet insufficiently investigated and consequently their true potential is not known.

Coal measures in Indonesia are principally of Eocene and Miocene age. Most have similar depositional histories, having been formed within intramontaine basins or deltaic environments. Coal beds in the various deposits have been ameliorated to different degrees by depth of burial, dynamic metamorphism and thermal gradients of igneous origin, thus giving rise to deposits of various ranks, form lignite to anthracite.

Indonesia has the second largest coal resource in Southeast Asia--only China has more coal than Indonesia. The total resource is estimated to be in the order of 32 000 Mt. Exploration for coal is continuing and this figure is expected to increase in the future. The Government of Indonesia is actively promoting expansion of the coal mining industry. A government sponsored coal mining company, PT Bukit Asam, has signed development contracts with a number of international and domestic companies to explore and develop coal deposits. These contracts have resulted in substantial foreign investments in the coal industry of Indonesia.

Sumatra has the largest known resource, estimated at 22 000 Mt, of mostly lignitic coal. Kalimantan ranks second with 8 000 Mt of higher rank and better quality coal. Coal on other islands contributes approximately 5% of the total resource. Typical coal quality parameters are:

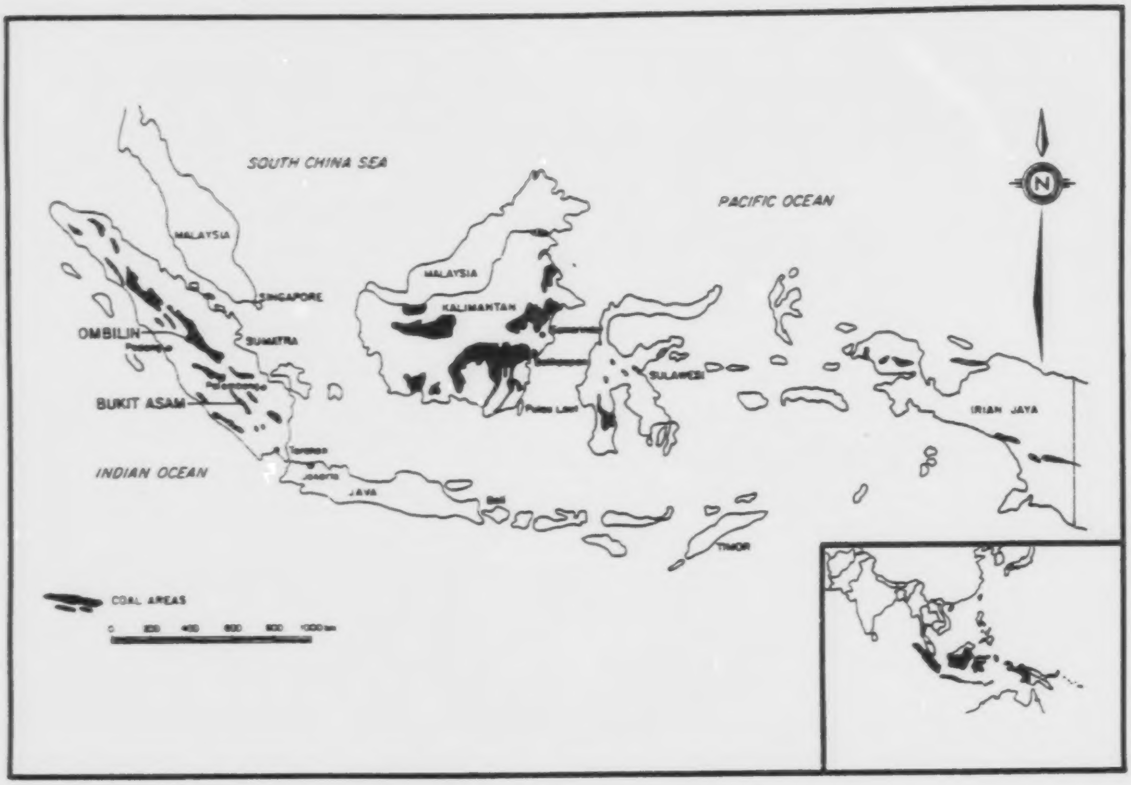
SOUTH CHINA SEA
PACIFIC OCEAN
N
MALAYSIA
SINGAPORE
MALAYSIA
KALIMANTAN
OMBILIN
SUMATRA
SULAWESI
Palembang
BUKIT ASAM
Pulau Laut
IRIAN JAYA
Tanjung
INDIAN OCEAN
Jakarta
JAVA
Bali
TIMOR
COAL AREAS
0 200 400 600 800 1000 km

Figure 9. Principal coal areas of Indonesia

	Air Laya (Sumatra)	Kaltim Prima (Kalimantan)
Moisture	24 %	9.5%
Ash	7 %	4 %
Sulphur	0.5%	0.5%
Calorific Value	5 300 kcal/kg	6 760 kcal/kg

Coal mining in Indonesia has more than a hundred years of history, having begun with the establishment of the Dutch East Indies coal mines in Sumatra during the last century. By 1940 the annual output has reached 2.03 Mt. The industry went into a decline during World War II, and by the early 1970's, production of coal had come to a virtual halt. Since then, following a slow start, coal mining has seen a revival and the annual coal production has climbed from 0.21 Mt in 1975 to 10.6 Mt in 1990. It is projected to reach 40 Mt by the year 2000. This goal is very much dependent on developing suitable offshore markets for Indonesian coal.

The market outlook for Indonesian coal in Southeast Asia, a region with some of the fastest growing economies in the world today, is good. Coal is being sold to electric power companies in Japan, trial shipments of coal for testing have been sent as far away as South America. Coal from Indonesia has also been solid in the U.S.A.

Domestically coal in Indonesia has a market in the generation of electric power and in industrial sector, principally in cement industry. The current level of power generation requires around 4.8 Mt of coal annually, and the cement industry in 1990 consumed an estimated 2 Mt.

The first coal mines in Indonesia were underground operations in Sumatra, but now the bulk of its coal is produced from surface mines. Nevertheless, underground mining is still a significant component of the industry; two rehabilitated longwall mines at Ombilin currently have a combined annual output of 0.6 Mt. The surface operations are mostly truck and shovel operations. An exception is the Air Laya pit at Bukit Asam where bucket wheel excavators are used.

THE PHILIPPINES

The Philippines, a Southeast Asian island nation, has a population around 60 million spread out over more than 7 000 islands, comprising a land area of approximately 797 000 km^2. Eighty percent of the people dwell on four main islands: Luzon, Mindanao, Negros and Cebu. Luzon alone accounts for more than 50% of the total population. The natural resources base of Philippines includes coal deposits that are found on a number of islands throughout the archipelago.

Coal deposits in the Philippines are of Eocene to early Pliocene age and originated under varied conditions in restricted

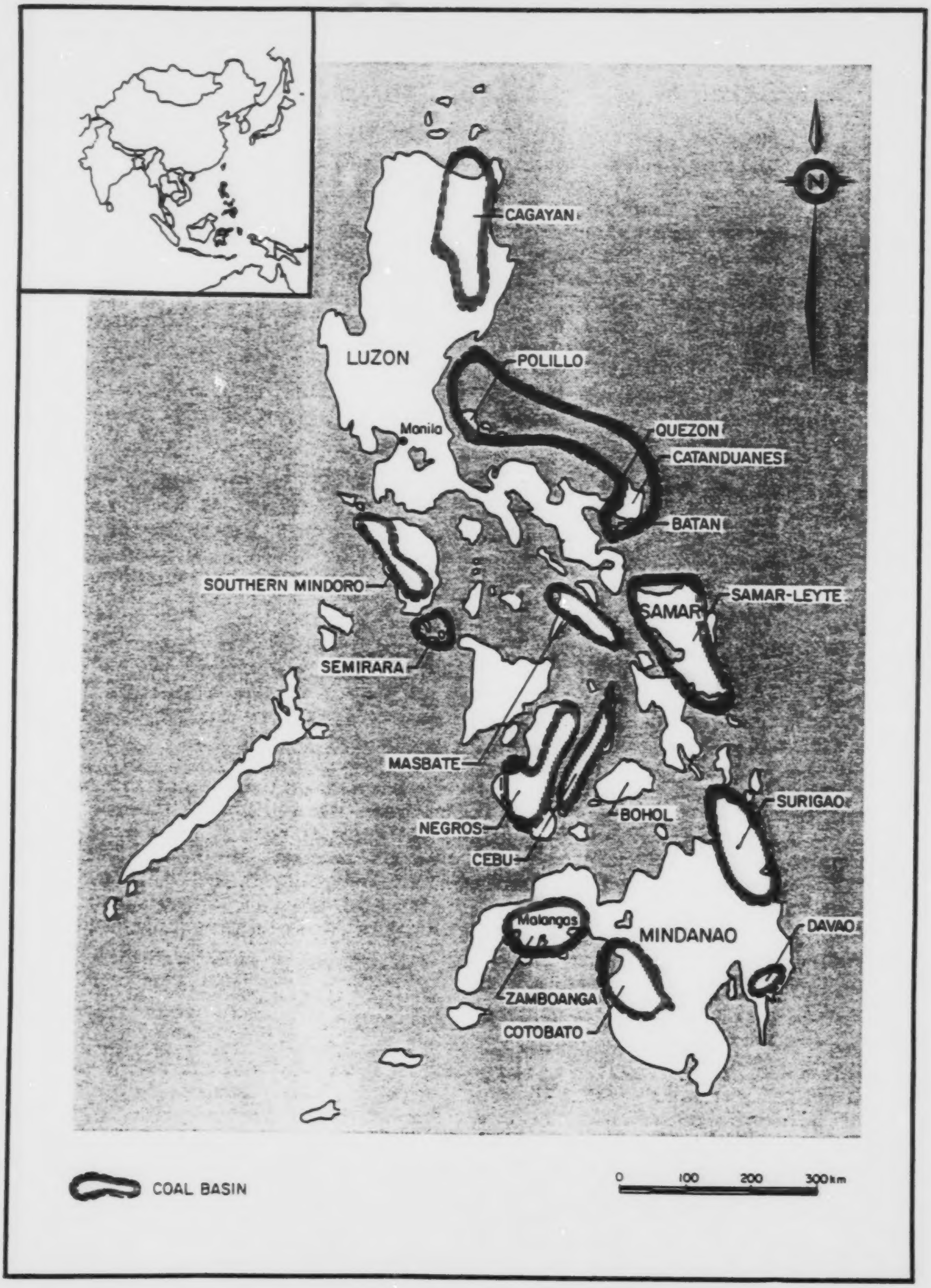
CAGAYAN
LUZON
POLILLO
Manila
QUEZON
CATANDUANES
BATAN
SOUTHERN MINDORO
SAMAR
SAMAR-LEYTE
SEMIRARA
MASBATE
BOHOL
NEGROS
CEBU
SURIGAO
Malangas
MINDANAO
DAVAO
ZAMBOANGA
COTOBATO
N
COAL BASIN
0
100
200
300km

Figure 10. Coal areas / basins of the Philippines

structural basins along the margin of an unstable shelf. The coal bearing strata generally are strongly folded and faulted. Because of their respective depositional environments, the coal seams show considerable lateral and vertical variations in extent and composition. The rank is also highly variable, the most common being high volatile subbituminous and lignite. Some deposits have been subjected to considerable dynamic stresses and volcanic metamorphism, which in some instances have increased the rank of the coal to bituminous.

The total estimated coal potential of the Philippines is quite large, in the order of plus or minus 1 700 Mt. The problems are the distribution of the larger deposits, which largely occur in the sparsely populated ares of the country, and the fact that tectonics have created difficult or impossible mining conditions.

The largest coal deposit [illegible] on Semirara island, a small speck of land off the southern tip of Mindoro island. Semirara is approximately 17 km long and only 5 km wide at its widest point. Nevertheless, there are three recognized coal deposits on the island, one presently being mined and two in the planning stages. The total coal resource of the island is around 550 Mt, of which 132 Mt are proven. There are at least six mineable seams, and the lower two are consistent in all three deposits. The deposits are badly faulted, and the principal mineable seams of the most northern deposit subcrop under the offshore coral reef. The rank of the Semirara coal is lignitic to subbituminous.

The next largest resource is the lignite deposit in the Cagayan Valley at the northern tip of the Luzon. The size of the resource is estimated at 334 Mt and 65 Mt are considered as proven. Where explored, the deposit has two principal coal seams, each averaging 1 m in thickness. The island of Mindanao has four coal regions with a total estimated resource of 433 Mt, but only about 45 Mt proven. The deposits are badly disturbed, are accessible only underground and have limited mining potential. It is the best quality coal in the Philippines, though.

The ash and heat contents of the Semirara coals are 16%-22% and 4 400 to 5 500 kcal/kg, and the comparable values for the Mindanao coals are 11%-13% ash, and heat values as high as 7 300 kcal/kg. The reported values for the lignite in Cagayan Valley are 15%-18% ash and 3 800 to 5 400 kcal/kg.

Coal has been mined in the Philippines for many years, but modern mining methods have been applied only during the past decade. The initial mining was on the island of Cebu, where a number of deposits have been mined in small underground mines under complex and difficult mining conditions. A modern mine using BWE equipment was opened on Semirara in 1984. Small retreat underground longwall mines are in operation in Mindanao. Coal production in the Philippines has grown from 0.3 Mt in 1980 to 1.2 Mt in 1990. Presently there are some 30 coal mines in the Philippines, but the single pit on Semirara alone contributes about one-half of the total production in the country.

The energy sector in the Philippines is heavily dependent on imported oil, and the government is striving to replace this expensive commodity with coal. The present coal consumption in the energy sector alone is about 2.5 Mt annually, making the country to a large degree dependent on coal imports. Therefore developing domestic supply sources is a high priority with the Government of the Philippines.

ACKNOWLEDGEMENTS

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NOTES

COAL AND THE ENVIRONMENT

Giacomo Capobianco
Coal Association of Canada

Although critics might suggest coal and the environment is an oxymoron, the truth is the world use of coal is increasing and the technology for using it safely and cleanly is well established. Canada represents a 'best case scenario' for the responsible use of coal - from mining to combustion.

NOTES

GEOLOGY, MINEABILITY AND COALBED GAS POTENTIAL OF THE DOUGLAS COAL ZONE IN THE NANAIMO COALFIELD, VANCOUVER ISLAND

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Robert Wilson, Georgia L. Hoffman
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Calgary, Albeta
T2S 2B3

ABSTRACT

For the past twenty years the Nanaimo Coalfield on Vancouver Island has been generally believed to be worked out, and it has only been since the beginning of natural gas and coalbed gas exploration in this area that the potential for remaining resources of coal has been appreciated. The Douglas Coal Zone is a group of five coal beds which are present in the eastern, previously unworked, portion of the Nanaimo Coalfield. The Douglas Coal Zone is gassy, and has been notorious for its local propensity to spontaneous outbursts of gas and coal into mine workings. The coal beds and their associated gas are of commercially attractive quality.

INTRODUCTION

The coals of the Douglas Coal Zone in the Nanaimo coalfield (Figure 1) have long been notorious for their difficult mining conditions. High gas contents of the coals, and their local propensity for spontaneous outbursts of gas and coal from mine faces and borehole walls, have impeded the large-scale development of underground coal mines at Nanaimo. With the recent advent of practical technology for coalbed demethanation, the gas associated with the Douglas Coal Zone has become a potential source of energy and an exploration target in its own right.

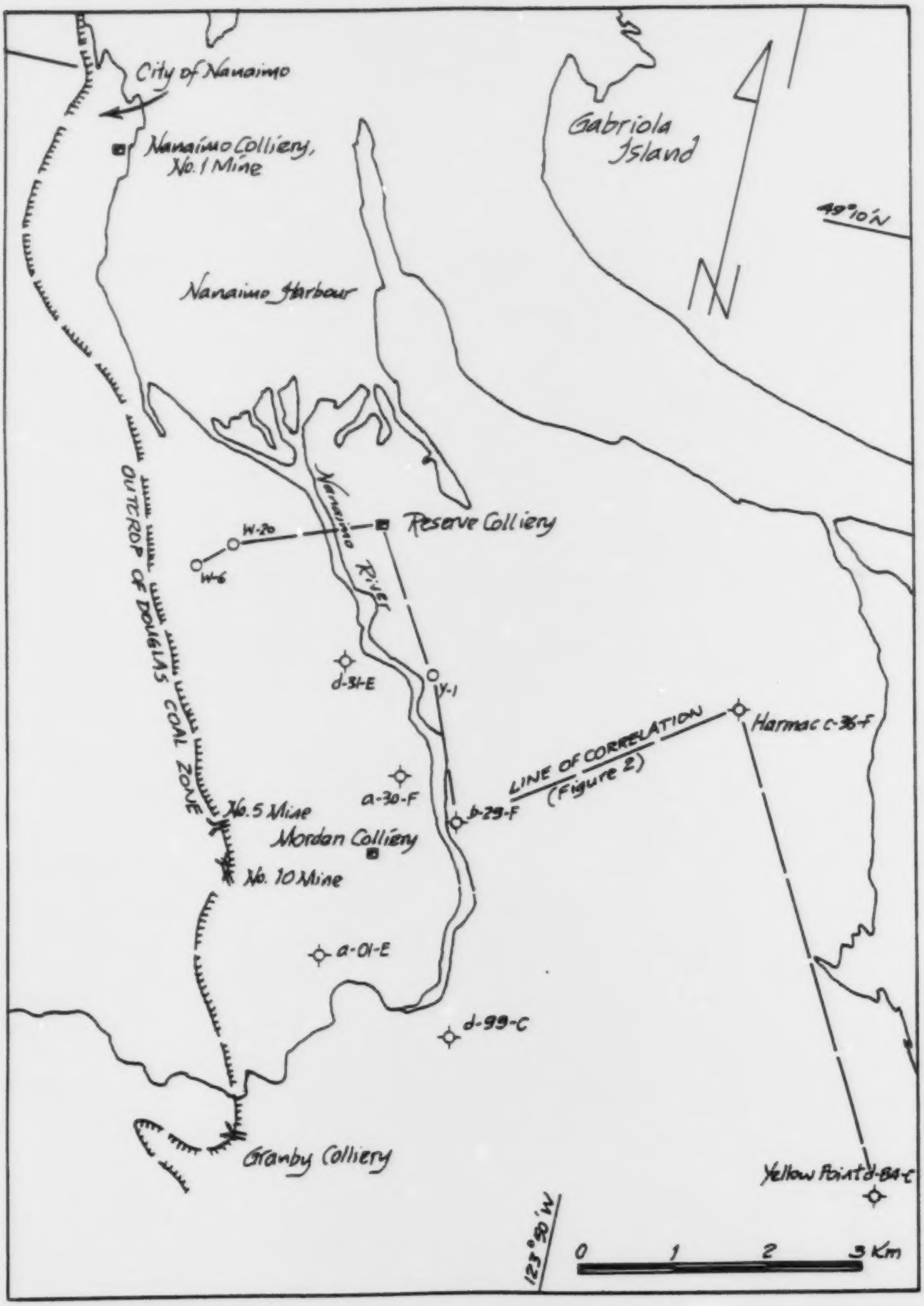
Most of the accessible shallow coal has now been mined out, and the remaining reserves lie at depths greater than 300 metres. Deep drilling and Vibroseis reflection profiling in the Nanaimo Coalfield has shown that the coal deposits may extend to depths as great as 1500 metres. Although such deep coals are beyond the foreseeable reach of conventional underground mines, they are well within the practicable depth range of coalbed gas production.

This paper will present the geology and resource potential of the Douglas Coal Zone in light of recent exploration results.

COAL-MEASURES STRATIGRAPHY

Coal beds in the Nanaimo coalfield are contained within four formations of the Upper Cretaceous Nanaimo Group. In ascending order these are the Comox, Extension, Pender and Protection Formations.

The Douglas Coal Zone within the top half of the Pender Formation has provided the bulk of historic coal production in the Nanaimo coalfield, and has the greatest potential for future developments as a source of coal and coalbed gas. Although the Extension coals have been extensively worked during the past 120 years, they do not appear to extend beneath the eastern half of the Nanaimo coalfield and they constitute an insignificant target for underground coal mining and coalbed gas production. The Comox and Protection coals have not been previously mined and appear to be either too thin or at too great a depth to present attractive prospects for coal development.


City of Nanaimo
Nanaimo Colliery, No. 1 Mine
Gabriola Island
49°10'N
Nanaimo Harbour
Nanaimo River
Reserve Colliery
W-20
W-6
d-31-E
Y-1
LINE OF CORRELATION (Figure 2)
Harmac c-36-F
OUTCROP OF DOUGLAS COAL ZONE
No. 5 Mine
a-30-F
b-29-F
Mordan Colliery
No. 10 Mine
a-01-E
d-99-C
Granby Colliery
Yellow Point d-84-C
123°50'W
0
1
2
3 Km

○ Coal exploration borehole

⌖ Gas exploration well (abandoned)

Figure 1: Index Map

DEFINITION OF THE DOUGLAS COAL ZONE

The Douglas Coal Zone consists of the four coal beds within the Pender Formation. In descending order, they are the Douglas Rider Seam, which is near the middle of the Newcastle member, the Douglas Seam, the Newcastle Seam, which defines the base of the Newcastle member, and the Cranberry Seam, within the uppermost part of the Cranberry member.

The Douglas Rider Seam appears to pinch out to the east. The Douglas and Newcastle Seams coalesce in the southeastern part of the Nanaimo Coalfield, forming the Douglas Main Seam. The Douglas Main Seam in turns appears to split further to the southeast, towards Yellow Point. The Cranberry Seam may merge northwards with the Newcastle Seam. Figure 2 depicts the relationships amongst these four coal beds, along a northwest-southeast traverse through the Nanaimo Coalfield.

DOUGLAS RIDER SEAM

The Douglas Rider Seam lies 10 to 25 metres above the Douglas Main Seam; as noted above, it appears to pinch out to the east. The Douglas Rider was locally known by mine operators as the Overlap or River Seam. In the workings of the South Wellington No.10 Mine, and the Cassidy (McKellar) No.7 Mine, the Douglas Rider consists of 1.5 to 2.1 metres of dirty coal with many bands of black coaly mudstone. The roof and floor of the Douglas Rider Seam are usually mudstone.

DOUGLAS MAIN SEAM

The Douglas Main Seam is the thickest coal bed of the Nanaimo coalfield, with an average thickness of 2.5 metres. The Douglas Main is notorious for rapid fluctuations in its thickness, from less than 30 centimetres to as much as 21 metres (Figure 3). Changes in thickness of the coal are mostly due to local folds and rolls in its floor, which are particularly pronounced near its outcrop at South Wellington (Graham, 1924). The main roof of the Douglas Main is usually mudstone, although 30 to 60 centimetres of hard ferruginous siltstone or cherty gritstone occasional form a false roof immediately over the coal. The floor of the seam is usually siltstone or silty mudstone. The Douglas Main Seam was deposited in a protected lagoon on the landward side of a storm beach. Isolated patches of mudstone within the main body of coal may have been deposited in lakes and ponds, while more extensive areas of mudstone may have been deposited in deeper water was not amenable to the growth of peat-forming vegetation. A complex pattern of erosional washouts of the coal represents the courses of streams which crossed the swamps.

The Douglas Main Seam splits to the northwest. The upper leaf of the split coal retains the name Douglas while the lower member is known as the Newcastle Seam. The line of split has been fairly well defined by means of surface and underground drilling (Figure 3). At the north end of the coalfield, the line of split lies just east of the eastern shore of Protection Island, then passes under Nanaimo Harbour towards the Nanaimo River delta. From there it describes a sinuous course southwestward to South Wellington, where it passes beyond the present outcrop of the coal. The line of split is again present in a syncline south of Cassidy, and appears to continue generally southward into a sparsely-drilled area near Nanaimo Airport.

The Douglas Main Seam is dissected by a complex pattern of erosional washouts within and between the workings of Morden Colliery and the South Wellington No.10 Mine. Adjacent to the washouts, which are up to 260 metres wide, the coal splits and pinches out into hard bluish-grey sandy shale. Boreholes in the channel belt show shale with thick interbeds of conglomerate and sandstone, and very thin, irregular stringers of coal, 8 to 15 centimetres thick. The uneroded thickness of the Douglas Main Seam in the washout area is 2.1 metres, but anomalous thickening to 4.5 metres occurs adjacent to the channel margins of washouts (McEvoy, 1921). Such marginal thickening of the coal may be due to large-scale rafting and redeposition of eroded peat. Taking into account the erosion and local thickening of the coal, the average thickness of the Douglas coal in the washout belt is about 1.04 metres (Buckham, 1944).

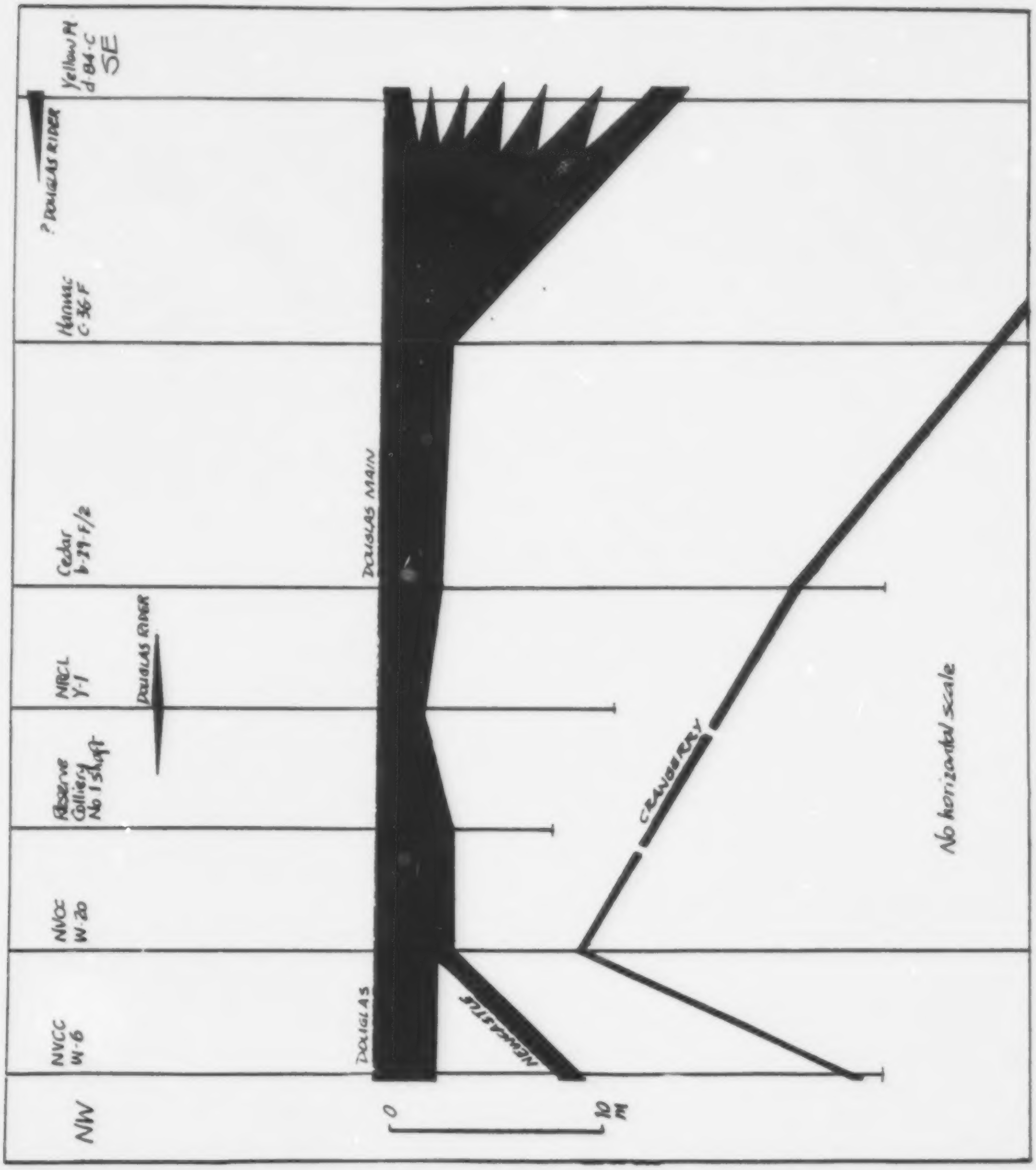

NW
NVCC W-6
NVOC W-20
Reserve Colliery No 1 Shaft
NRCL Y-1
Cedar b-29-F/2
Hannac C-36-F
Yellow Pt d-84-C
SE
? DOUGLAS RIDER
DOUGLAS RIDER
DOUGLAS MAIN
DOUGLAS
NEWCASTLE
CRANBERRY
No horizontal scale
0
10 m

Figure 2: Correlation of coals of the Douglas Coal Zone

On the south side of Reserve Colliery, the Douglas Main Seam pinches out unpredictably, and reappears as an underlapping or overlapping coal bed at a vertical interval of 3 to 10 metres. This feature is probably due to minor thrusting of the coal measures, but it could be due to zig-zag splits within the coal, which are the result of the complex depositional interaction of meandering streams and peat mires (Ward, 1984).

The Douglas Main Seam is generally sheared and is therefore friable and often devoid of recognizable cleat systems. Thin bands of black shale are interspersed throughout the Douglas Main Seam towards the limits of its mineable extent, presaging splits in the bed. Otherwise the coal tends to be clean and finely banded, consisting mainly of desmocollinite and vitrodetrinite with minor amounts of resinite and locally substantial amounts of disseminated and interlaminated clay.

DOUGLAS SEAM

The Douglas Seam is on average about 2 metres thick (Figure 3), although it locally pinches and swells from 60 centimetres to 4.5 metres thick. Changes in the thickness of the Douglas Seam are primarily due to the irregular depositional topography of its floor. The roof of the Douglas Seam is usually mudstone, although gritstone forms the roof in some localities near downtown Nanaimo. The floor of the seam is usually hard pebble-conglomerate. The Douglas Seam was deposited on the landward (southward) face of a storm beach. Complex topography on the top of the gravelly beach deposits was probably formed by the modification of beach ridges by tidal channels.

Finely-striated, dull and bright to bright banded coals predominate in the Douglas Seam. The coal locally grades laterally into isolated patches of black, coaly mudstone. Such stone pods, known by the old miners as 'silted areas' are particularly abundant along the northeastern and eastern edges of the old workings of the No.1 Mine of Nanaimo Colliery under Nanaimo Harbour (Watkin Evans, 1928 and 1932) The Douglas Seam usually consists of hard, blocky coal with a well-developed system of cleats. Douglas coal has a low to moderate ash content, ranging from 8 to 13% on dry basis. It consists mainly of desmocollinite and vitrodetrinite with minor amounts of resinite, disseminated clay and interlaminated clay.

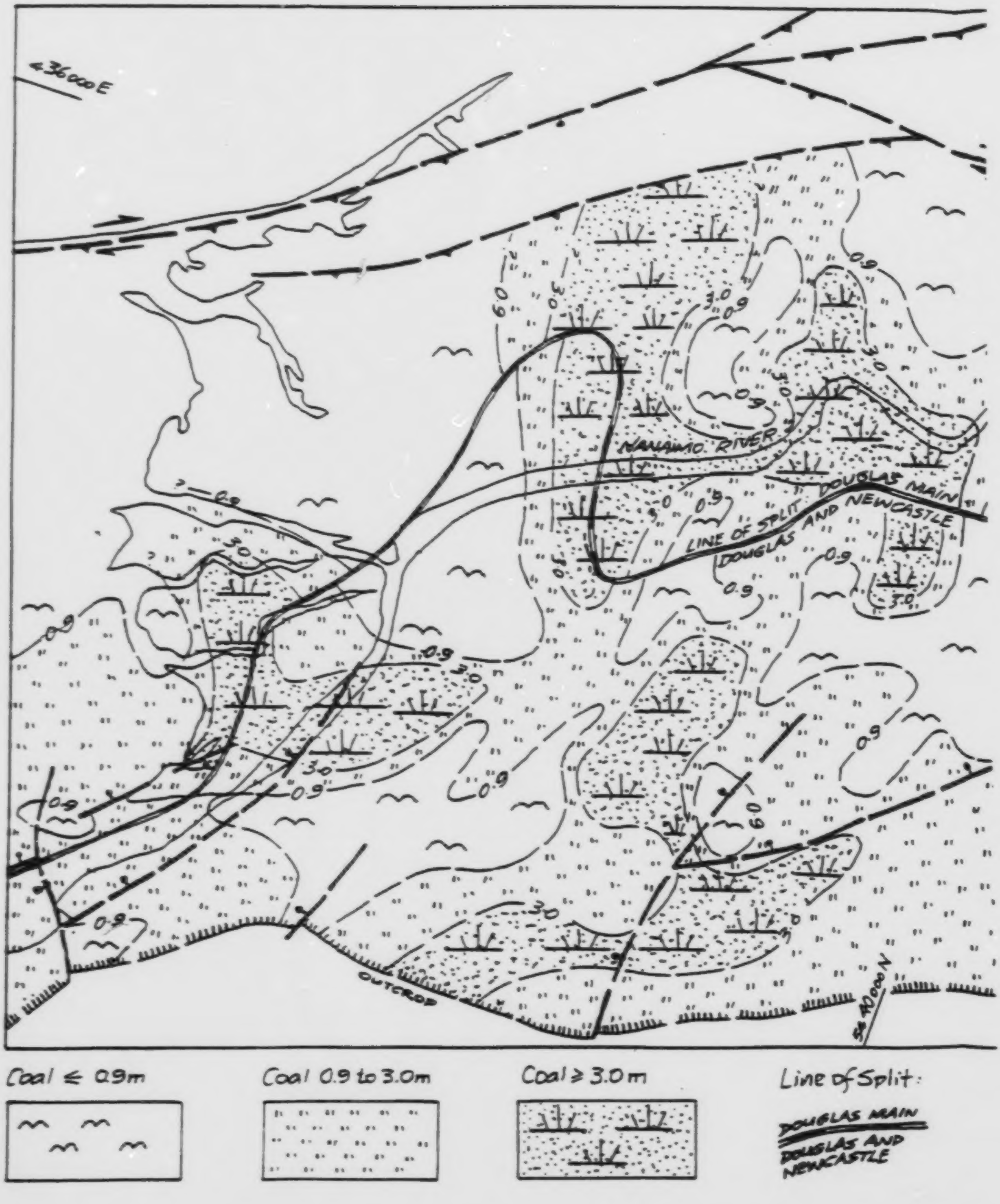
NEWCASTLE SEAM

The Newcastle Seam, where present, lies 15 to 30 metres below the Douglas Seam. In the Nanaimo coalfield, the Newcastle Seam is generally less than 1 metre thick, and usually contains several partings of mudstone and hard siltstone. The Newcastle Seam is locally represented solely by a zone of black coaly shale. The roof of the Newcastle Seam is usually very hard pebble-conglomerate which contains molluscs including Inoceramus. A false roof of up 1.2 metres of platy silty sandstone locally intervenes between the coal and the base of the conglomerate. The floor of the Newcastle Seam is usually soft mudstone or silty mudstone. The Newcastle Seam was deposited in a salt-marsh environment, overlying delta-front mudflats and in turn overlain by gravelly beach deposits.

The Newcastle coal has a slightly higher content of inertinite-group macerals (chiefly inertodetrinite) and a lower content of liptinite-group macerals, as compared with the Douglas coal. The Newcastle coal is generally bright banded, with a well-developed cleat structure. In contrast to the pervasive shearing of the Douglas Seam, most of the bedding-plane shear in the Newcastle Seam has been taken up by its included dirt partings. On the whole the Newcastle coal is therefore blockier and stronger than the Douglas Main coal.

CRANBERRY SEAM

The Cranberry Seam lies 10 to 15 metres below the Newcastle and Douglas Main Seams. Very few boreholes in the Nanaimo coalfield have been drilled deep enough to intersect the Cranberry Seam, so little is


436000E
NANAIMO RIVER
LINE OF SPLIT
DOUGLAS MAIN
DOUGLAS AND NEWCASTLE
0.9
3.0
6.0
OUTCROP
5440000N
Coal ≤ 0.9m
Coal 0.9 to 3.0m
Coal ≥ 3.0m
Line of Split:
DOUGLAS MAIN
DOUGLAS AND NEWCASTLE

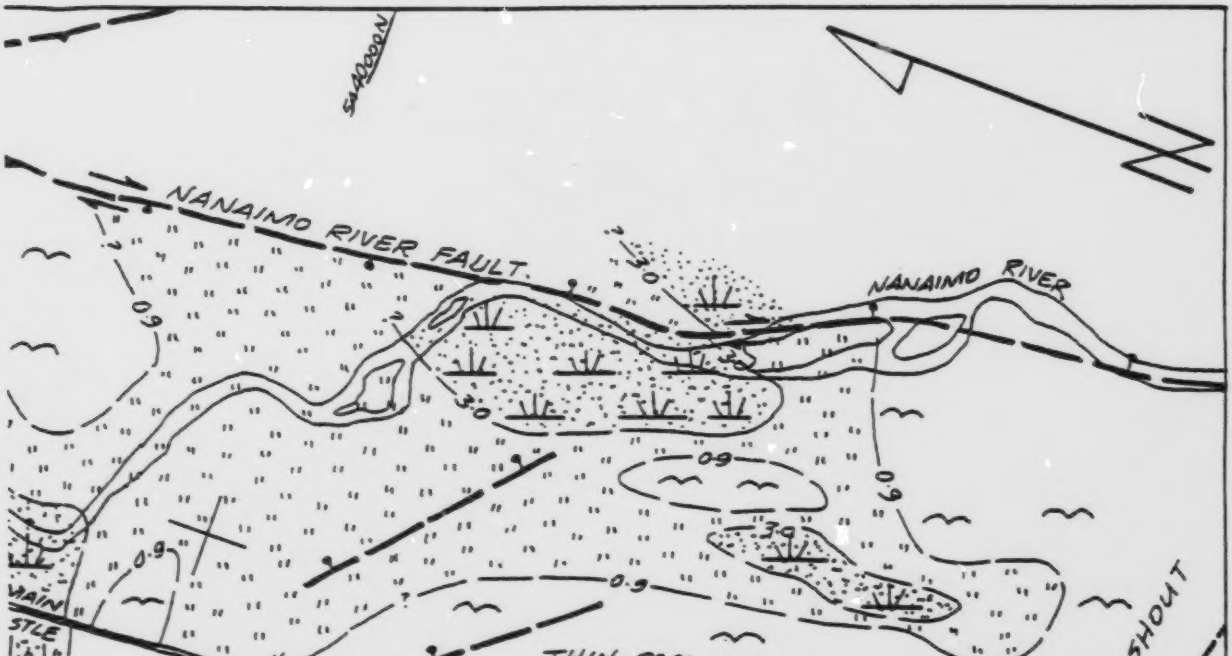

5440000N
NANAIMO RIVER FAULT
NANAIMO RIVER
3.0
0.9
THIN COAL AND SHALE
WASHOUT
WASHOUT
WASHOUT
LINE OF SPLIT DOUGLAS MAIN SEAM
DOUGLAS AND NEWCASTLE SEAMS
MAIN
STLE
436000E
OUTCROP
0
1
2 Km

Figure 3: Gross thickness map of the Douglas and Douglas Main Seams

yet known about its lateral persistence. The coal bed is 20 to 60 centimetres thick, and consists mainly of clean coal with a few partings of coaly mudstone and siltstone. The roof and floor of the Cranberry Seam are usually mudstone or siltstone. No petrographic data are available for the Cranberry Seam.

COAL QUALITY

Table 1 presents proximate analyses of the coal seams within the Douglas Coal Zone, derived from reports by Clapp (1914), Lewis (1910), Greenwald (1922), McEvoy (1921), and others. Nearly all of the available analyses are of face samples taken underground, or of mine run production.

TABLE 1: AS-RECEIVED ANALYSES OF THE DOUGLAS COAL ZONE

Coal bed:	M:	VM:	FC:	Ash:	Sulphur:	BTU:
Douglas Rider						
(2 analyses)						
Mean:	2.26	37.16	46.06	14.53	0.53	11959
Minimum:	1.50	32.51	42.91	7.50	0.50	10501
Maximum:	3.02	41.80	49.20	21.56	0.56	13417
Douglas Main:						
(16 analyses)						
Mean:	2.32	32.63	48.44	16.95	0.63	12254
Minimum:	1.00	22.90	41.90	6.58	0.43	10457
Maximum:	7.15	42.12	59.72	33.50	1.07	13306
Douglas:						
(6 analyses)						
Mean:	2.55	36.79	52.14	8.53	0.82	12849
Minimum:	1.60	29.20	47.43	5.62	0.28	12552
Maximum:	3.98	40.97	57.40	10.70	1.28	13266
Newcastle:						
(3 analyses)						
Mean:	2.65	32.28	54.48	10.59	1.06	11903
Minimum:	2.40	27.80	45.48	8.95	0.82	11332
Maximum:	3.15	40.50	59.35	11.61	1.27	12474
Cranberry:						
(1 analysis)						
Mean:	1.14	33.45	45.73	19.68		

The Douglas Rider coal is of High Volatile A bituminous rank. The Newcastle and Douglas coals are of High Volatile C bituminous rank in the northern part of the coalfield, increasing southwards to High Volatile B bituminous. The Douglas Main coal is of High Volatile A bituminous rank, possibly increasing at depth to Medium Volatile in the southern part of the coalfield, while insufficient data are available to determine the rank of the Cranberry coal.

In comparison with the Carboniferous coals of the Appalachian coal province, the Cretaceous coals of the Nanaimo Coalfield are fairly dirty, due to the presence of fine-grained intergrowths of clay and organic matter. Petrographic compositions of the coals of the Nanaimo Group are fairly consistent. All of the coals have high vitrinite contents, which is consistent with their bright banded appearance in hand specimen.

STRUCTURAL GEOLOGY

The coal measures of the Nanaimo coalfield are gently warped into a series of southeasterly-plunging broad open folds (Figure 4). Limb dips range from 5 to 12 degrees over most of the area while regional dip is about 8 degrees northeast. A major north-striking transcurrent fault, known as the Nanaimo River Fault, cuts through the centre of the Nanaimo coalfield. Its trace roughly follows the lower reaches of Nanaimo River, to the east of the workings of Morden Colliery. Actual breaks of the coal-measures are rare (Buckham, 1944; 1947); instead, the Nanaimo River Fault is expressed as a series of asymmetric rolls, stepping down to the east and north, bordered by a zone of steep (40 to 75 degrees) easterly and northeasterly dips. Displacement across the Nanaimo River Fault is difficult to assess. Minor shear structures in outcrop indicate that the fault has a component of dextral strike-slip shear. The apparent vertical offset of the Douglas Seam is 60 to 120 metres down to the east.

Several southwest-dipping thrust faults have been mapped in the Nanaimo coalfield. Vertical displacements at the horizon of the Douglas Coal Zone are probably in the range of 30 to 90 metres down to the northeast. Mine plans also indicate the presence of numerous minor tensional and compressional faults in the Douglas Coal Zone. The intensity of minor faulting appears to decrease from north to south.

GAS CONTENT OF THE DOUGLAS MAIN SEAM

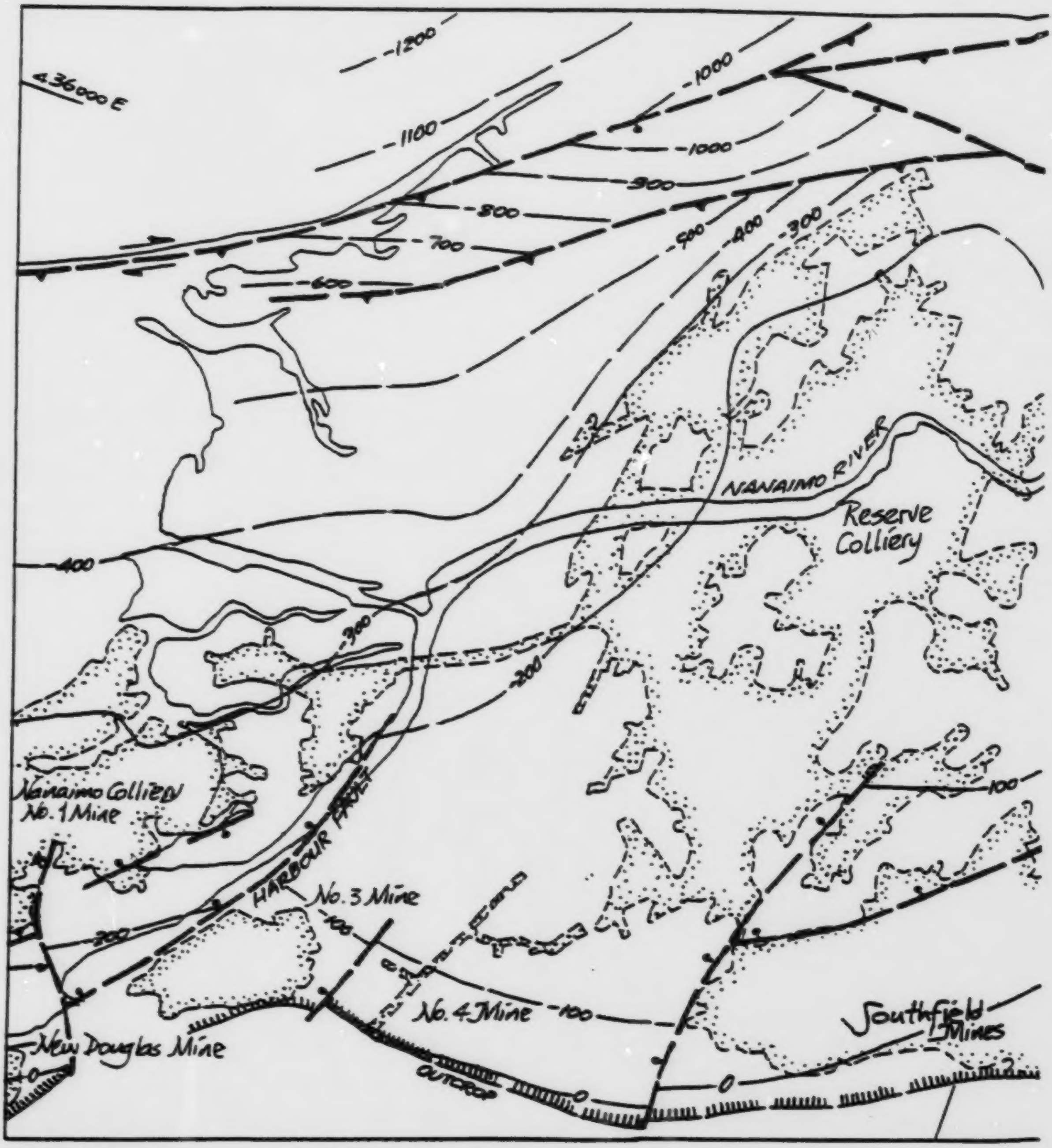
Desorbtion tests of coal cores from boreholes drilled near Morden Colliery show the desorbable gas content of the Douglas Main Seam to be 5 to 12 cubic metres per tonne (Murray, 1986; Kenyon and Murray, 1990; Proudlock, 1990). Douglas Main gas contains 95.05% methane, 4.42% higher hydrocarbons, and 0.53% carbon dioxide; this is acceptable quality for delivery to a gas transmission system. (Kenyon and Murray, 1990).

Table 2 presents typical gas emission rates for some of the deep coal mines of Vancouver Island, as reported by the British Columbia Minister of Mines.

TABLE 2: GAS EMISSION RATES IN VANCOUVER ISLAND COAL MINES

Mine:	Coalfield:	Year:	Coal Bed:	Average depth of cover (m):	Gas emission rate (cubic metres/tonne):
Reserve	Nanaimo	1918	Douglas Main	300	8.8
Morden	Nanaimo	1918	Douglas Main	250	23.8
Number Five	Comox	1918	Comox No.1	200	17.2
Number Five	Comox	1935	Comox No.2	300	128.1
Number Four	Comox	1918	Comox No.4	250	64.5

In evaluating the gas content of a coal bed on the basis of mine air analyses, it should be kept in mind that gas emission rates from coal mines are a function of the desorbable gas content of the coal, permeability of the coal and its roof and floor strata, and rate of coal production from the mine. Kissell and others (1973) have suggested that for extensively-worked, deep coal mines, a fairly constant relationship exists between the desorbable gas content of virgin coal and rate of emission of gas from the mine. They consider that 6 to 9 times as much gas is emitted from such coal mines, as could be accounted for by direct desorbtion from the mined coal. The increased gas emission is probably due in part to migration of gas through the coal bed to the working faces and emission of gas from the roof and floor of the worked-out coal bed.


-1200
436000 E
-1100
-1000
-1000
-900
-800
-700
-600
-500
-400
-300
NANAIMO RIVER
Reserve Colliery
-400
-300
-200
Nanaimo Colliery No. 1 Mine
HARBOUR FAULT
No. 3 Mine
-100
-200
No. 4 Mine
-100
Southfield Mines
New Douglas Mine
0
OUTCROP
0
0
100
Old mine workings (generalized)
Structure contour on floor of Douglas/Douglas Main Seam
-100
Datum is mean sea level
Contour interval is 100 metres

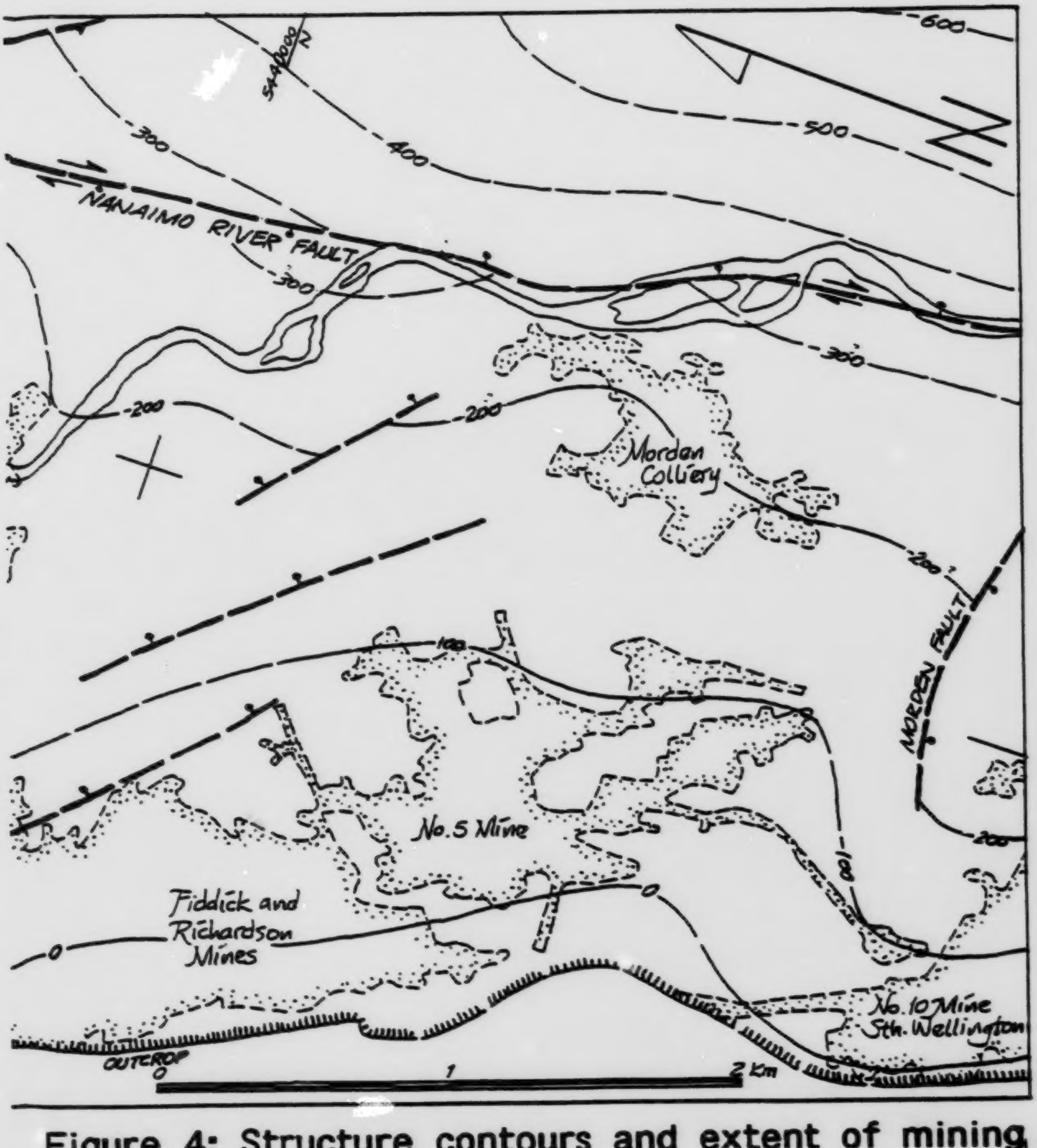

5446000 N
600
500
400
300
NANAIMO RIVER FAULT
300
300
200
200
Morden Colliery
200
MORDEN FAULT
100
100
No. 5 Mine
200
Fiddick and Richardson Mines
0
0
No. 10 Mine Sth. Wellington
OUTCROP
0
1
2 km

Figure 4: Structure contours and extent of mining in the Douglas and Douglas Main Seams

Emission rates of methane from Morden Colliery (Table 2), at an average of 23.8 cubic metres per tonne of mined coal, are approximately 2 to 4 times as high as the desorbable gas content of the coal cores, suggesting that either the Douglas Seam or its bounding strata may be relatively impermeable, as compared with the coal beds studied by Kissell and others (1973). Impermeable roof and floor strata may increase the likelihood of overpressured conditions in coal beds (Decker and Horner, 1987).

Although the Comox mines had higher gas emission rates than the Nanaimo mines, no spontaneous outbursts were reported from the Comox mines. Several factors may have contributed to this apparent anomaly. Firstly, the Comox coals were stronger and had well-defined cleats, while the Nanaimo coals tended to be sheared and friable. Secondly, the Comox mines were generally worked by longwall, while the room-and-pillar method was employed in the Douglas Main Seam at Nanaimo. Touhey (1923) reported that the incidence of outbursts appeared to be reduced following a change from room-and-pillar to modified longwall methods at the Granby Colliery in Nanaimo. Finally, the Comox coals are closely associated with thick, porous sandstones, which may have served to drain gas from the coal beds, while the Douglas Main Seam at Nanaimo is generally underlain and overlain by siltstone and mudstone.

Some preliminary work was done by Polak and Pierlot (1972) towards an assessment of the potential for gas production or gas storage in the mine workings near Nanaimo. The feasibility of gas storage in the old mine workings is limited owing to the extensive interconnection of the mines by cross-measure tunnels. The abandoned Morden Colliery appears to have the best potential for such use.

HYDROGEN SULPHIDE EMISSIONS

Hydrogen sulphide has been encountered from the Douglas Seam in the workings of several mines, including the No.1 Mine of Nanaimo Colliery and Reserve Colliery (James, 1969). In all cases the concentration of hydrogen sulphide appears to have been quite low, as its major impact upon the mining operation was to cause irritation of the eyes and lungs of the coal miners.

Only the shallow (less than 200 metres) near-outcrop portions of the Douglas Seam were reported to contain hydrogen sulphide. Sour gas has not been reported from any of the coalbed gas or conventional gas test wells at Nanaimo. The shallow sour gas in the Douglas Seam is probably of biogenic origin, due to bacterial transformation of sulphides and sulphates in the organic-rich black shales above the Douglas Seam.

EXPLORATION HISTORY

The first and most extensive campaign of mineral exploration on Vancouver Island was directed towards the delineation of mineable coal deposits. The Hudson's Bay Company brought the first drill rig to Vancouver Island in the 1860's. Following the sale of the Hudson's Bay coal mines to English capitalists in the 1870's, at least 210 boreholes were drilled in the search for new coal reserves. Interpretations of borehole and mining records by engineers and geologists led, by 1914, to the basic recognition of the stratigraphic and structural style of the Cretaceous coal measures of the Nanaimo coalfield. (Ashworth, 1912; Baker, 1904; Clapp, 1914; Morison and Forster Brown, 1910; McCallum, 1909).

Natural gas was first encountered in coal exploration boreholes in the mid 1920's. About 5% of the subsequent boreholes at Nanaimo encountered notable flows of gas or artesian salt water.

Intensive exploration for natural gas in the Nanaimo coalfield commenced in 1982, when BP Canada conducted a regional geochemical and geological survey. Favourable results of this survey led to a follow-up programme of reflection seismic surveys in 1984 and 1985, subsequent acquisition of oil and gas rights, and the drilling of two exploratory wildcat gas wells near Nanaimo in 1986.

The first of these wells, Harmac c-36-F, encountered the Douglas Main Seam at a depth of 610 metres. The Harmac well was plugged and abandoned after drillstem testing indicated the presence of salt water in a sandstone reservoir.

The second well, Yellow Point d-84-C, encountered 14 metres of interbedded shale and coal, correlative with the Douglas Coal Zone, at a depth of approximately 1018 metres. The Yellow Point well continued into the Comox Formation, where it encountered gassy coal, at least three metres thick, at a depth of approximately 1570 metres. The coal blew out into the well bore, causing the well to be abandoned due to stuck tools. The Yellow Point well is significant in that it was the discovery well for Comox coal in the Nanaimo Coalfield. Prior to the drilling of the well, the Comox coals had not been thought to be present in the Nanaimo coalfield.

BP's two wells were probably technical successes, in that they proved the existence of gassy coals in the deeper portion of the Nanaimo coalfield. The wells were, nevertheless, economic failures, in that no conventional gas-charged reservoir rocks were encountered, and neither drill-stem nor desorbtion tests were carried out on the coals.

At the same time as BP was conducting its search for natural gas, Novacorp International Consulting Ltd. commenced an intensive programme of coalbed gas exploration at Nanaimo. Novacorp drilled seven boreholes in search of the Douglas Main Seam during 1984 and 1986 (Murray, 1986.) Five wells reached the Douglas Main Seam, and cores of coal for desorbtion tests were recovered from two wells. Commercial production was not established owing to shortage of funds on the part of Novacorp and the local land-owner (Kahil, 1990).

In 1986, BP and Novacorp both abandoned their efforts on Vancouver Island, BP because their two exploratory wells were economic failures, and Novacorp because the firm decided to close down their coalbed methane department. Since 1986, gas exploration on Vancouver Island has been confined to desk studies of individual structures by small companies. The Douglas Main Seam remains the major exploratory target for coalbed gas at Nanaimo, although the deeper coal of the Comox Formation merits further attention.

MINING HISTORY

Coal mining at Nanaimo commenced in 1849, and reached its peak development in 1921. The last large deep mine (No.10 Mine at South Wellington) closed in 1952, largely due to ventilation problems related to the high gas content of the Douglas Main Seam, and mining has since been concentrated along the western edge of the coalfield, where the coals lie under shallower cover.

Gas emissions from coal mines became a serious problem in the 1920's, with the advent of deeper and more rapidly-advancing mine workings. Spontaneous outbursts of gas and coal in Douglas Main Seam caused several fatalities and limited development of parts of the Nanaimo coalfield, particularly south of Cassidy (Baird, 1944; Rice, 1922 and 1931; Strachan, 1942; Touhey, 1923; Wilson and Henderson, 1927). In the interests of safety, further southward development work in the Douglas Main Seam at Cassidy was prohibited by the Chief Inspector of Mines (Wilkinson, 1926; British Columbia Minister of Mines, 1927).

The depth of onset of outburst conditions decreases from north to south in the Nanaimo coalfield. No outbursts were encountered of the Nanaimo Colliery No.1 Mine under Nanaimo Harbour, which worked to depths as great as 550 metres. Outbursts occurred in the Reserve Colliery at depths greater than 300 metres. In No.10 Mine at South Wellington and Granby Colliery at Cassidy, outbursts were encountered at depths greater than 240 metres. The southward rise of the outburst limit may reflect a southward increase in the shearing of the Douglas Coal Zone.

The Douglas Rider, Douglas Main and Douglas Seams were usually worked by the room-and-pillar method. This method gave fair results at depths as great as 550 metres, despite increasingly difficult strata control problems and the high gas content of the coal. Rooms and crosscuts were driven 2.4 to 3.0 metres wide, on 25 to 45 metre centres. The pillars thus formed were taken out on retreat, and good use was made of the panel system to isolate areas of thick, friable coal which were prone to spontaneous combustion. The double-stall method was used to a limited extent, in areas where the coal was either very thick or very dirty.

Classical hand-filled longwall faces were worked in the thin Newcastle Seam. During the 1930's, increasing used was made of the semi-longwall method, where straight faces were worked along predetermined lines of advance. Semi-longwall faces were equipped with mechanical coal cutters and pan-conveyors.

Timber in generous quantities was used for roof support. Systematic timbering rules were adopted in most of the mines working the Douglas Main Seam, in light of its particularly treacherous roof. The Nanaimo mines closed before such necessities of modern mining as roof bolts and continuous miners became readily available.

ASSESSMENT OF MINEABILITY OF DEEP COAL BEDS AT NANAIMO

Remaining mineable reserves of the Douglas Main Seam lie at depths of 300 to 750 metres. Based on past experience at Nanaimo, the coal will be extremely gassy, susceptible to outbursts of gas and coal, and may be prone to spontaneous combustion. Any mining method must be capable of contending with these problems along with those posed by undulating floor rocks, weak sheared coal, and rapid variations in seam thickness.

The depth of the coal effectively rules out access to the reserves by means of cross-measures drifts from surface, while the great distance from the outcrop to the reserves rules out easy access by slope entries within the Douglas Main Seam. Shafts are therefore the preferred method of access, despite their high capital and operating costs. Hoisting shafts should be located at the deepest point in the reserve area, while ventilation shafts should be located to the rise, in the interests of efficient ventilation. Pre-drainage of a portion of the coalbed gas by means of production wells from the surface can be expected to lower the mining costs by reducing the amount of gas entering the ventilations system of the mine. Pre-drainage of coalbed gas should also provide valuable geological data in advance of mining, as well as offering the chance to recover costs by selling the gas to the local pipeline utility company.

The geological complexity of the Douglas Main Seam will probably make longwall mining uneconomic. Room-and-pillar mining, as practiced in the past, may be successful, although the floor of the Douglas Main Seam may not be suitable for the imposition of heavy equipment loads. Recoveries from roof-and-pillar mining are unlikely to exceed 50% of the coal in place.

Greater recoveries may be obtainable through hydraulic mining of the coal. The hydraulic method is capable of dealing with weak coal, although its success will depend on the effectiveness of geological forecasting of irregularities in the floor of the seam, as well as the amenability of the roof to caving after the coal has been extracted. The hydraulic method will limit the exposure of workers to the hazard of outbursts from the working faces. Outbursts may still present problems during development of production headings in the coal.

Depending on the amount of water produced from the coal seam, and the size consist of the mined product, it may be beneficial to consider dewatering of the coarse coal at the shaft bottom, and hoisting of the coarse coal in skips.

The practical minimum thickness for room-and-pillar mining in the Douglas Main Seam will be about one metre, while hydraulic mining will probably require a minimum thickness of 1.35 metres. Room-and-pillar mining of coal thicker than 3.5 metres will require that some form of rib support be used, while seams up to 15 metres thick should be workable by hydraulic mining.

CONCLUSIONS

The Douglas Main Seam in the Nanaimo coalfield has a desorbable pipeline-quality gas content of 5 to 12 cubic metres per tonne. Biogenic hydrogen sulphide occurs in the near-outcrop portions of the Douglas Main and Douglas Seams. Hydrogen sulphide has not been encountered in any of the coal beds tested in the gas wells at Nanaimo.

Old mine workings at Nanaimo have a limited potential for the production of accumulated gas, and as gas storage units. Morden Colliery has the highest potential for such development, since its workings are not connected to those of other collieries.

Previous attempts to develop gas prospects at Nanaimo have failed due to lack of available capital, and lack of effective testing of some of the wells.

Remaining mineable reserves of the Douglas Main Seam may be recoverable by means of hydraulic mining. Further studies must be done to assess the applicability of this mining method to the deep coals of the Nanaimo coalfield.

ACKNOWLEDGEMENTS

We thank Bob Bone, Inspector of Mines at Nanaimo, for allowing us to examine the detailed plans of the Nanaimo mines. Without these plans we would still think that there was no mineable coal left in the Douglas Coal Zone. Brian Young at the British Columbia Archives and Records Service, the archivists at the Glenbow-Alberta Institute Archives, Barb Lemke at the Cumberland Museum and Candace Kenyon at the British Columbia Geological Survey found ancient drill records for us. Dick Marshall, Stan Lawrence and Win Pearson have kept us honest over the years, whenever we waxed optimistic about how far we could go in mining thin coal beds. The errors and mistakes in this paper are the cherished property of its authors.

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NOTES

PEACE RIVER COALFIELD DIGITAL MAPPING PROGRAM

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The Peace River coalfield digital mapping program is a 1:50 000-scale mapping and compilation project in northeastern British Columbia being carried out by the Coal Unit of the B.C. Geological Survey Branch. Work on the project in 1991/1992 involved mapping of the Carbon Creek area (93O/15) and Le Moray Creek area (93O/8) to produce geologic maps for publication as Open File maps in January 1992. An important aim of this year's work was to integrate the use of geographical information systems (GIS) with field mapping.

The data gathered in the field were combined with information compiled from previous Open File publications, coal assessment reports and petroleum borehole data, into a computer database. QUIKMap, GIS software designed for use on a microcomputer, provided the means to combine, organize, edit and display the information. TRIM digital map data produced by the Ministry of Crown Lands was used to produce base maps in QUIKMap. By combining the compiled data and the field data using QUIKMap, the computer becomes an interactive tool in the field, as opposed to merely an electronic file cabinet for geologic data.

The database will be used in conjunction with QUIKMap software and TRIM base-map data to generate computer-drafted geology maps of the Carbon Creek and Le Moray Creek areas. With the maps and data in digital form, it will be possible to distribute the computer files containing finished maps that would include the edited and refined data, as well as files containing all the original raw data used in drawing the maps. Downstream users will have the option of examining and manipulating all the data using their own software packages.

NOTES

GEOCHEMISTRY OF CARBONIFEROUS COALS FROM SPRINGFIELD COALFIELD, NOVA SCOTIA

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The depositional environment of late Carboniferous coals from Nova Scotia was formed in both localized intermontane and extensive regional basins. The intermontane coals occur in multi-seam sequences and were developed in a rapidly-subsiding, elongate basin. The coals in regional basins are laterally extensive over the large area.

The B (boron) content of coal is either 1) primary and due to the influence of the environment of deposition and is in agreement with other geological evidences of 2) is due to a secondary enrichment. The higher B content (190 ppm) in some Nova Scotian coals deposited in the intermontane setting (primary B: 50 ppm) is often due to secondary enrichment and is related to the occurrence of Lower Carboniferous evaporite deposits and diapirs, extensive fault systems associated with the coalfields, and the activity of groundwater. For example, coal seams from the Springhill coalfield, Cumberland basin were developed in an inland river valley setting bordering a piedmont of mature, (coalesced) alluvial fans, derived from the Cobequid highlands to the south. Shales associated with these coal seams are of fresh water origin. During deposition of this major coal-bearing assemblage, peat-forming ecosystems 4 to 7 km in width flourished along a margin of advancing coalesced alluvial fans. The successive peatlands became increasingly dependent on the piedmont as a source of ground water recharge as the basin infilled and groundwater supply became more restricted.

Both gypsum and salt are present in the Springhill coalfield and the formation of the Springhill anticline is probable related to the displacement of these evaporites. The geochemistry of coal seams particularly their B content is related to the location of the seam, which in turn, might be influenced by groundwater circulation. The B content of coal in the piedmont zone near the Cobequid Highland massif is 36 ppm, in the range of freshwater coals elsewhere, which indicated true primary B content for these coals. The direction of groundwater circulation is controlled by surface topography and both local and regional recharge and discharge zones. In the recharge zone, the seams did not encounter upwelling waters from the basin. These coals have low B content (36 ppm) associated with their depositional environment. In contrast, the high concentration of B in the inner mire (190 ppm) and riverine (210 ppm) zones is secondary in nature and probably is due to addition of B from dissolved evaporites by groundwater and discharge of the brine into these areas of the coal seams.

NOTES

GEOCHEMISTRY OF COALS AND ASSOCIATED SEDIMENTARY ROCKS FROM ELK VALLEY COALFIELD, BRITISH COLUMBIA, CANADA

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Coal seams from outcrops and active mines in the Elk Valley Coalfield of British Columbia were analyzed for their maceral composition, using reflected light and geochemistry, using AA, INNA and ICAP. Detailed elemental analyses were carried out for: a) coal and the sedimentary parting within a number of selected coal seams, b) coal seams in equivalent sections and c) for all coal seams across the coalfield.

There is no marine influence in the Elk Valley Coalfield as indicated by geology and sedimentology, however the coal seams are deposited in a freshwater, upper delta setting and mildly brackish, lower delta - coastal plain setting.

There is a decrease in concentration of Al, As, Sc, Th and the rare earth elements for the coal bands in a seam, while the concentration of these elements in sedimentary parting remain almost constant or increase from roof to the floor. The concentration of the elements associated with minerals (clay and/or carbonate) such as K, Mg, Na, Sb, Th, U, V, and Zn for coal seams in the coal bearing strata follow similar trends, indicating that the mode of coal formation is often cyclic for example there are three cycles in the Eagle Mountain section and two in the Greenhills section in the Fording Coal mine.

The elements Al, B, Ba, Ca, Cr, Fe, Mg, Mn, K, Si, Na, Sr, Ti, V and Zn, are the only elements to show significant range differences between the coal sections, as determined by standard deviation of the elemental average for the coal seams. The concentration of some elements such as Ca is highly variable (500 - 37 000 ppm).

The elemental content of coal seam is related to the lithology of the roof and floor sediment. The coal enclosed by the siltstone/shale contain higher K, Na, Rb, and Cs than the coal enclosed by sandstone/siltstone roof and shaley floor. The permeability of sandstone allows the movement of groundwater into the coal seam during the early stages of coalification, resulting in the concentration of certain elements including Ba, Ca and Sr.

Elk Valley coal seams contain low average concentration (in ppm) of environmentally sensitive elements: B (20), Cl (52), S (1.0%), As (1), Mo (2), Pb (5), Se (3), U (1.5).

When geochemistry of coal seams compared for different parts of coalfield, it is found that the elemental composition amongst the seams from sections located in the central area are similar, while those in the western limb of Alexander Creek area syncline are very similar. The only notable differences between these two areas is slightly less Ba in the west limb and slightly more Mn in the east limb. The northern coal seams have different geochemistry from the rest. These seams have much more As, Br, Cr, Cu, Fe, K, and Na, however they contain less Ca.

GEOCHEMISTRY OF BOWRON RIVER COAL DEPOSIT, BRITISH COLUMBIA

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The Bowron River coal deposit is located in east-central British Columbia in the intermontane region. The coal measures are Tertiary in age, occur in the Bowron River graben and are bounded by Mississippian age volcanics. The B (boron) content of this deposit, as determined on the coal seams and layers from a drillhole (#GSB-90-01), is between 65-125 ppm and is higher in the upper part of the coal deposit. The variations in B and As contents for coal from this drillhole indicates that the high B content for the coal seams/layers is not a reflection of the depositional environment, which was limnic swamps near the shores of a shallow lake. Rather, it is related to the removal and mobilization of As, B and S from the Mississippian volcanics occurring in the area possibly by groundwater circulation through the faults and into the coal beds. The As content of the Bowron River coal is between 2-123 ppm with an average value of 27 ppm, which is higher than the averages of other intermontane coal deposits from British Columbia such as Hat Creek (12.7 ppm) or Tulameen (2.7 ppm).

NOTES

GEOCHEMISTRY OF BORON IN AUSTRALIAN AND CANADIAN COALS

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ABSTRACT

The concentration of boron in Australian and Canadian coals was determined using Atomic Emission (AGES),Inductively Coupled Plasma Spectrometry (ICP) and Prompt Gamma Ray (GP) Spectrometry in order to assess the variation of B content in coal with respect to rank, age, geological setting (in seam and stratigraphic) and degree of paleosalinity of coal forming environment.

This study indicates that no and/or very complex relations exist between boron and rank (sub-bituminous to anthracite). Variations of B with ash content for Canadian coals of different age (Devonian to Oligocene-Eocene) indicate that B content of coals is not governed by the age of the coal.

There is some evidence of variation of B with maceral content in Canadian coals, particularly as related to the inertinite content of coals.

After a reappraisal of earlier work, and on the basis of recent work on Australian coals and Canadian coals, it is proposed that the following ranges of values for B in coal indicate the various degree of marine influence on original peat swamps:

up to 50 ppm B: freshwater-influenced coals
50 to 110 ppm B: mildly brackish-influenced coals
>110 ppm B: brackish-influenced coals

Using these criteria, assessments are given for the degree of marine influence on Canadian and Australian coals.

INTRODUCTION

There is boron data for a wide range of coals from Australia (Clark and Swaine, 1962; Brown and Swaine, 1964; CSIRO, 1960, 1966; Bone and Schaap, 1981; Knott and Warbrooke, 1983; Davy and Wilson, 1984; Swaine et al., 1984b), Canada (Hawley, 1955a; Goodarzi, 1987a & b,1988; Goodarzi and Van der Flier-Keller, 1988, 1989; Goodarzi and Goodbody, 1990), New Zealand (Kear and Ross, 1961), South Africa (Kunstmann et al, 1963) and the USA (Zubovic et al, 1964, 1966; Swanson et al., 1976; Gluskoter et al, 1977; Zubovic et al., 1980; White et al., 1983; Chou, 1984; Affolter and Stricker, 1987). The content of boron in most coals "would probably be between 5 and 400 ppm B" (Swaine, 1990). The present study examines the relationship between boron content of Australian and Canadian coals with their environment deposition, rank and age.

DETERMINATION OF BORON

The determination of B in coal has been carried out by the following methods: atomic emission spectrometry (AES),(Zubovic et al., 1961) using a direct current arc or an inductively coupled plasma emission spectrometry (ICPAES), (Pollock, 1975) and by special technique using prompt gamma-ray spectrometry (GP), (Gladney et al., 1976).

CONTENTS OF B IN COAL

The contents of B in some coals are given in Table 1. There is a complete compilation of the contents of B in coals of different ranks from various countries (Swaine, 1990, Goodarzi and Swaine, in press). Low-rank coals from Hat Creek (Canada), East Germany, and Victoria (Australia) had low B contents (2-32 ppm B), but higher values have been reported for some Leigh Creek, South Australia and USA coals. A similar situation is found with bituminous coals, where low and high values may occur, even in one area. In some areas there is a remarkable consistency in B contents. For example, 13 samples from 9 locations in the Lithgow seam, western part of the Sydney Basin, Australia had 15-30 ppm B with a mean of 20 ppm B (for 90% of values), the samples being taken over a distance of about 100 km (Swaine, 1984).

a) Rank Relationships.

The detailed studies of B in Canadian coals indicate that there is a complex relation between boron and rank of coals from the same age and geological setting for example: there is no relation between B and rank for coal examined within a coal-bearing section/or strata, i.e. high to medium volatile bituminous coal (% Ro$_{max}$: 0.85-1.35) from Fording coal mine; (Goodarzi, 1988) or medium volatile bituminous to semi anthracite, % Ro$_{max}$: 1.30 - 2.50, (Figure 1), (Goodarzi and Cameron, 1987); same age and different geological setting (Banerjee and Goodarzi, 1990), and different age and geological setting (Goodarzi, 1987a; Goodarzi and Van der Flier-Keller, 1989). Table 1 shows the variation of B content with rank (lignite - meta anthracite) for Canadian coals. These coals are of different age and depositional environment. Hat Creek coal (A zone), from British Columbia and coal from seam #3, Vesta mine and seam # 0 from the Horseshoe Canyon Formation, Drumheller coal area, Alberta, are sub-bituminous (% Ro$_{random}$: 0.38-0.50), (Goodarzi, 1985a; Gentzis et al. 1990). However, Hat Creek, which was deposited in a freshwater environment, has B content of <50 ppm, while Vesta and Drumheller coals, both influenced by brackish conditions, have B content of 150 and 675 ppm.

b) Age Relationships.

The variation of B content with ash content for Canadian coals of different age (Devonian to Oligocene- Eocene) is shown in figure 2. It is apparent that the B content of coals is not governed by the age of coal. For example, coals from Hat Creek,

Table 1. Contents of B in some coals (as ppm B)

Low-rank coals (lignite-subbituminous):		
Latrobe Valley, Victoria	2-30	(Bone and Schaap, 1981)
Leigh Creek, South Australia	40-300	(CSIRO, 1966)
Hat Creek No. 1, BC, Canada	9-32	(Goodarzi, 1987a)
Hat Creek No. 2, BC, Canada	5-18	(Goodarzi and Van der Flier-Keller,1988)
Saskatchewan, Canada	15-234	(Beaton 1990)
Niederrhei, East Germany	6-21	(Pietzner and Wolf, 1964)
Gulf Province, USA	<10-200	(Swanson et al, 1976)
Fort Union region, USA	15-300	(Hatch and Swanson, 1976)
Greece	8-444	(Foscolos et al, 1989)
Bituminous coals:		
Sydney Basin, NSW	1-300	(Clark and Swaine, 1962)
Bowen Basin, Queensland	<1.5-150	(Brown and Swaine, 1964)
Fording Mine, BC, Canada	9-94	(Goodarzi, 1988)
Byron Creek, BC, Canada	25-200	(Goodarzi, 1987b)
Telkwa, BC, Canada	18-40	(new data)
Vesta Mine, Alberta, Canada	171-265	(Gentzis et al 1990)
Manville, Alberta, Canada	18-1144	(Banerjee and Goodarzi, 1990)
Melville Island, Arctic Canada	14-69	(Goodarzi and Goodbody, 1990)
Ruhr, West Germany	9-91	(Kautz et al, 1975)
South Africa	11-109	(Kunstmann et al, 1963)
N. England, S. Wales	0.5-50	(D.J. Swaine, unpublished)
Eastern USA	<0.6-160	(Zubovic et al, 1980)
Western USA	16-140	(Gluskoter et al, 1977)
Alaska, N. Slope	20-200	(Affolter and Stricker, 1987)
Semi-anthracite		
Mount Allen, Alberta, Canada	9-30	(Goodarzi and Sawine in press)
Anthracite		
Hoidahl Dome Northwest Territories, Canada	5- 10	(Goodarzi and Swaine in press)

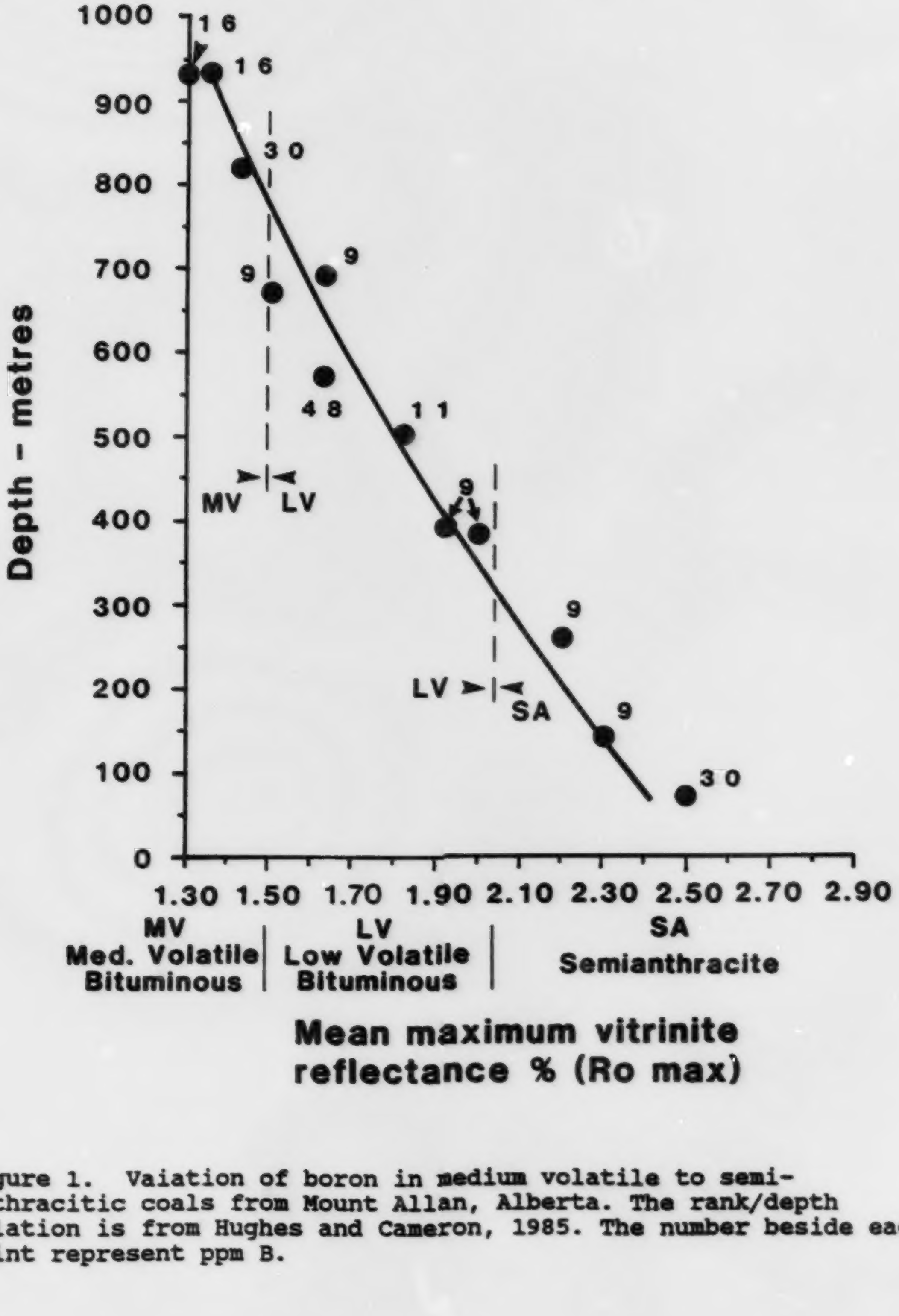

Figure 1. Vaiation of boron in medium volatile to semi-anthracitic coals from Mount Allan, Alberta. The rank/depth relation is from Hughes and Cameron, 1985. The number beside each point represent ppm B.

British Columbia (Oligocene-Eocene), Mount Allan, Alberta (Jurassic/Lower Cretaceous), Hoidahl Dome, Yukon Territories (Carboniferous) and Melville Island (Devonian) all have B content of < 50 ppm indicating their freshwater setting rather than their age.

c) Compositional Relationships.

An important factor which influences the composition of Canadian coals is the age of coal. Coals of differing ages may have different maceral compositions due to the various types of peat-forming plant communities which are age related (Teichmüller and Teichmüller, 1982). In Canada, the Devonian coals from the Arctic are sporinite-rich (Goodarzi and Goodbody, 1990), in contrast Cretaceous and younger coals are often resinite rich (Hat Creek coals, British Columbia, Goodarzi 1985). Unlike the Australian Gondwana coals which contain up to 85% inertinite (Chandra and Taylor, 1982, 1985), the Canadian coals may occasionally contain up to 35 % inertinite (Cameron, 1985).

There is some evidence of variation of B with maceral content in Canadian coals, particularly as related to the inertinite content. For example seam # 7 from Drumheller was deposited under mildly-brackish setting and has a B content of 70 ppm, while an inertinite band occurring on the top of this seam has B content of 27 ppm. The carbonaceous shale (ash content: 43 %) occurring immediately beneath this inertinite layer has also a B content of 35 ppm. The lower B content for this inertinite layer is accompanied by low S and a volatile matter contents and higher fixed carbon contents as compared to the whole coal (Table 2). A similar situation is observed in the in-seam study of seam # 3 from Vesta mine, Alberta (Table 2).

Table 2. Variation of boron with macerals in western Canadian coals.

Location	Rank	Depositional Environment	Ash yield (percent wt)	S (percent wt)	Fixed Carbon (percent wt)	B (ppm)
Drumheller area, Seam #7	Subbit.	Mildly brackish				
a. Inertinite rich layer			7.0	0.16	62	27
b. Carbonaceous shale			43.0	0.28	45	35
c. Whole coal			14.0	0.31	52	70
Line Creek 1. Seam #6	Med. vol. bit.	Freshwater				
a. Vitrinite rich layer			9.2	0.72	67.4	54
b. Inertinite rich layer			6.2	0.65	71.5	23
c. Whole coal seam			27.0	0.64	54.0	47

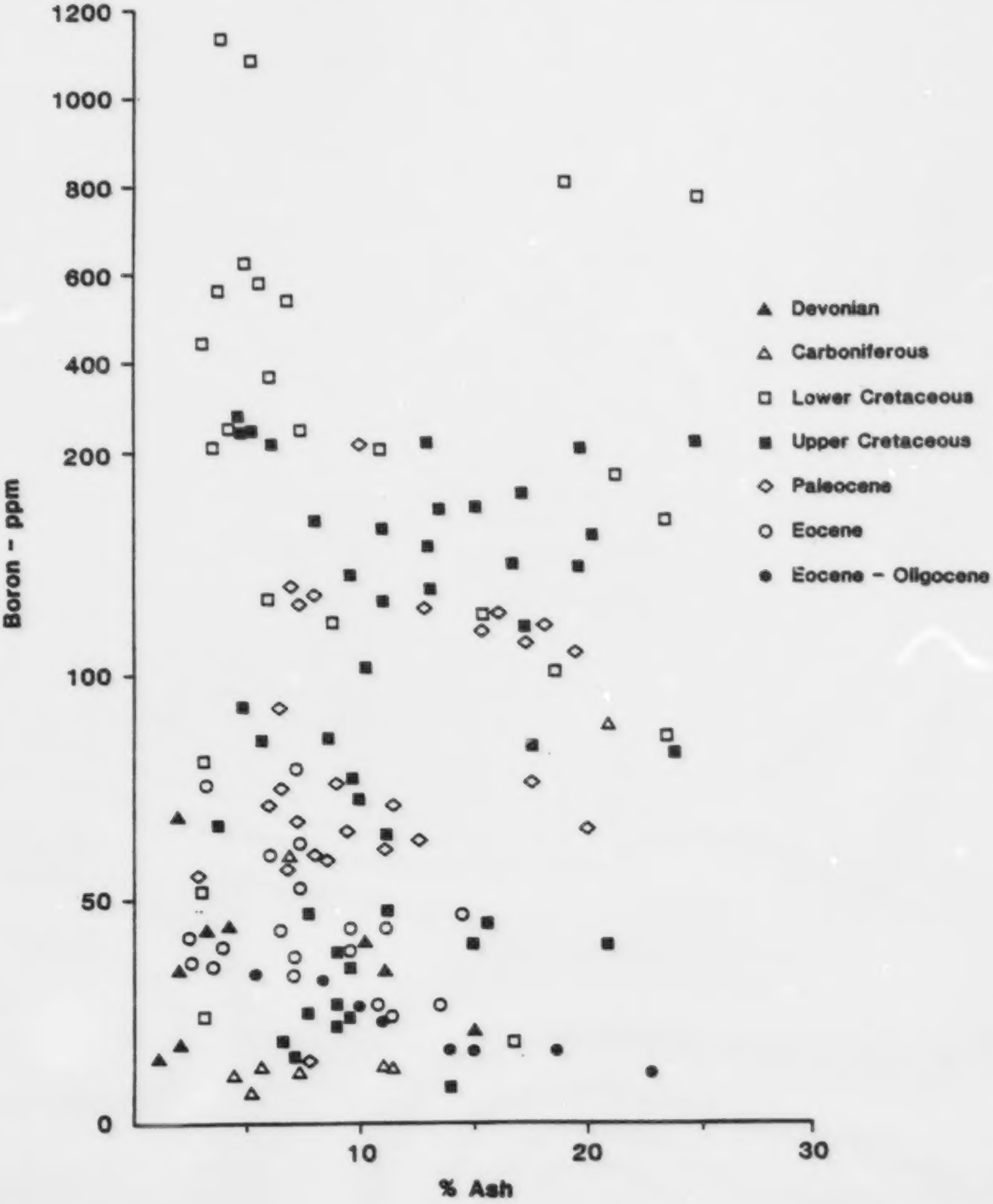

Figure 2. Variation of boron versus age of coals from Canada.

Goodarzi et al (in press) have reported a higher concentration of B (78 ppm) for a vitrinite rich band (ash yield: 6.0 %), as compared to the whole coal (average of 11 samples: 46 ppm) in seam # 8 from Line Creek mine, British Columbia (Table 2). The relatively higher B content of the vitrinite-rich layer possibly indicates an organic association of B.

Seam # 6 from Line Creek, British Columbia contains one vitrinite-rich and one inertinite-rich bands. The vitrinite band has a higher B content (54 ppm) than either seam average (B: 47 ppm), or the inertinite band (B: 27 ppm). Inertinite bands in coal are indicative of a drop in the water table level, and therefore dryness, oxidation and also possibly peat fires (Goodarzi 1985 b), while occurrence of vitrinite bands indicates a higher water table level. The low B content of inertinite-rich bands in seam #3 from Vesta mine and seam # 6 from Line Creek mine simply indicates the formation of these two bands above the water and therefore, less contact with water that contains B.

MARINE INFLUENCE ON B IN COAL

The basis for using B as marine indicator in clays, coals or other materials is that seawater has 4.6 ppm B compared with less than about 0.1 ppm B in most river and other terrestrial waters.

In view of the usefulness of B in clays for indicating, at least approximately, degree of salinity in terms of marine, brackish and freshwater, several attempts were made to use B in sediments associated with coals (Degens et al, 1957 and Keith and Degens, 1959). Bohor and Gluskoter (1973) used B in illite as an indicator of paleosalinity of Illinois coals, and suggested that better results would probably be gained by using samples from vertical sequences of cyclothemic units.

The above mentioned studies indicates that It is possible to assess the relevance of B in coal to the degree of marine influence. Hence, Swaine (1962a) determined B in hundreds of samples of coal (samples with an ash yield of less than 35%). He suggested that the Illawarra Coal Measures, Australia were freshwater-influenced and the Greta Coal Measures, Australia were marine-influenced, there being some independent geological evidence for these conclusions, for example, marine fossils are associated with *Glossopteris* in the upper beds of the Greta Coal Measures. The results for the Tomago Coal Measures indicate some influence from brackish conditions (Swaine, 1967), a finding that has some support from geological evidence (Diessel, 1965 and 1980). On the basis of these results and further work, it was suggested that the following scale of values is applicable (Swaine, 1971):

up to 40 ppm B: freshwater-influenced coals
40-120 ppm B: brackish-influenced coals
>120 ppm B: marine-influenced coals

The original term 'marine' could perhaps be misunderstood and could infer that the coal was formed in seawater, whereas the conditions of salinity were intermediate between seawater and freshwater, that is, brackish. As pointed out by Goodarzi

(1987a) "it is difficult to visualize a coal seam of any lateral extent or thickness developing in a true marine environment". However, some peat swamps occurred in proximity to the sea. Wanless et al (1969) suggested that "many coal swamps were near sea level and were subject to drowning with a slight rise in sea level". They cite examples of marine transgressions which would have produced brackish conditions during coalification in some parts of the USA. Following a reappraisal of earlier work and taking into account recent work by Goodarzi and coworkers on Canadian coals and by Swaine and coworkers on Australian coals, it is proposed to modify the B range and define environmental condition of deposition as:

up to 50 ppm B: freshwater-influenced coals (F)
50-110 ppm B: mildly brackish-influenced coals (MB)
>110 ppm B: brackish-influenced coals (B)

CONCLUDING REMARKS

The detailed studies of B in Canadian coals indicate that there is either no relationship or a very complex relation between boron and rank of coals from the same age and geological setting.

Variation of B content with ash content for Canadian coals of differing ages (Devonian to Oligocene-Eocene) indicates that the B content of coals is not governed by age. Coals from Hat Creek, British Columbia (Oligocene to Eocene), Mount Allan, Alberta (Jurassic/Lower Cretaceous), Hoidahl Dome, Yukon Territories (Carboniferous) and Devonian age coals from Melville Island, Arctic Canada all have B content of < 50 ppm indicating that B is related to that their freshwater setting is not to their age. However the lower rank coals (sub-bituminous to high volatile C/B) are more susceptible to secondary B enrichment.

There is some evidence of variation of B with maceral content in Canadian coals, particularly as related to lower B content in inertinite-rich coals.

An interesting use of B contents in coal is the estimation of the degree of marine influence. Coal is preferred to clays as an indicator of varying degrees of marine influence, that is salinity of swamp waters during the early stages of coalification.

Proposed Boron scale agrees well with established geological parameters and is a good tool to indicate depositional conditions, but would not help in determination of degree of secondary enrichment. degrees of marine influence on coals:

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SEISMIC CHARACTER OF COAL MEASURES, GULF OF ST. LAWRENCE REGION

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Exploratory wells in the Gulf of St. Lawrence region have penetrated coal zones of the Upper Carboniferous Pictou Group. Hacquebard (1986) correlated these zones with the coals of the Mabou and Inverness coal fields on the west coast of Cape Breton Island, and pointed out that this borehole evidence defines the Gulf of St. Lawrence Carboniferous Basin as the largest coalfield of eastern Canada. Study of multichannel and high resolution seismic data collected in the Gulf of St. Lawrence region supports this interpretation, and provides additional information regarding the present extent of the coal zones. Structural and character aspects of the seismic data also bear upon assessing the former extent of the coal basin. Mapping these Coal Measures enables speculative estimates of coal and coalbed methane resources.

NOTES

PHOSPHORUS IN BRITISH COLUMBIA COKING COALS

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ABSTRACT

The concentrations of phosphorus in raw and clean coal samples from the Mist Mountain Formation in the East Kootenay coalfields of southeast B.C., and the Gates and Gething formations in the Peace River coalfield of northeast B.C., have been compiled. Raw coals of the Mist Mountain Formation contain the highest mean phosphorus concentrations (0.076 per cent), Gething Formation coals are intermediate (0.063 per cent), and those of the Gates Formation contain the least (0.042 per cent). Phosphorus is mainly associated with the inorganic fraction of the coals. The principal factors controlling phosphorus contents in raw B.C. coking coals are the ash content and the types of accessory minerals. Most of the phosphorus in these coals is believed to be in apatite minerals, including fluorapatite.

There is no consistent stratigraphic trend in phosphorus contents in raw Mist Mountain Formation coals, although coals from the upper half of the formation appear to contain more phosphorus, on average, than those from the lower half. The basal part of the formation hosts coals with relatively low phosphorus contents. In raw Gates Formation coals there is a general up-section increase in average phosphorus concentrations. In all three formations the amount of data scatter within individual seams can be very pronounced.

A representative average of phosphorus concentrations in clean B.C. coking coals is 0.05 per cent.

INTRODUCTION

Phosphorus occurs in all coals in minor or trace amounts. Although it is not generally regarded as a pollutant, the concentration of phosphorus in a coal is an important parameter to coal users, particularly steel mills. This is because phosphorus in coke is taken up by steel in the blast furnace, and an excess of phosphorus in steel is detrimental to its quality. There is no universally accepted tolerance level for phosphorus in coking coal, and in some cases it is not a major concern. Other variables are equally or more critical, including the phosphorus concentrations in the iron ore, and the steel-making process used. Phosphorus content is also of interest to operators of some coal-fired boilers, because under certain conditions phosphate precipitates can form (Burchill et al., 1990).

In this study, phosphorus contents of British Columbia coking coals have been compiled, for the purposes of comparison and making preliminary conclusions concerning form(s) of association of phosphorus. Follow-up work will investigate the association of phosphorus in more detail.

Coking coal in British Columbia occurs in two regions, the Peace River or northeast, and the East Kootenay or southeast (Figure 1). In the latter region, economic coals belong to the Mist Mountain Formation of the Jurassic-Cretaceous Kootenay Group. There are currently four mines in the East Kootenay coalfields which produce coking coal; these are the Fording River, Balmer, Greenhills and Line Creek mines. A fifth mine, Coal Mountain, produces and markets weak coking coal. In the Peace River coalfield, major bituminous coal resources belong to the Gething Formation of the Lower Cretaceous Bullhead Group, and the Gates Formation of the Lower Cretaceous Fort St. John Group. There are two mines in the Peace River area, both of which produce coking coal. These are the Quintette and Bullmoose mines, and the coal in both cases is hosted by the Gates Formation.

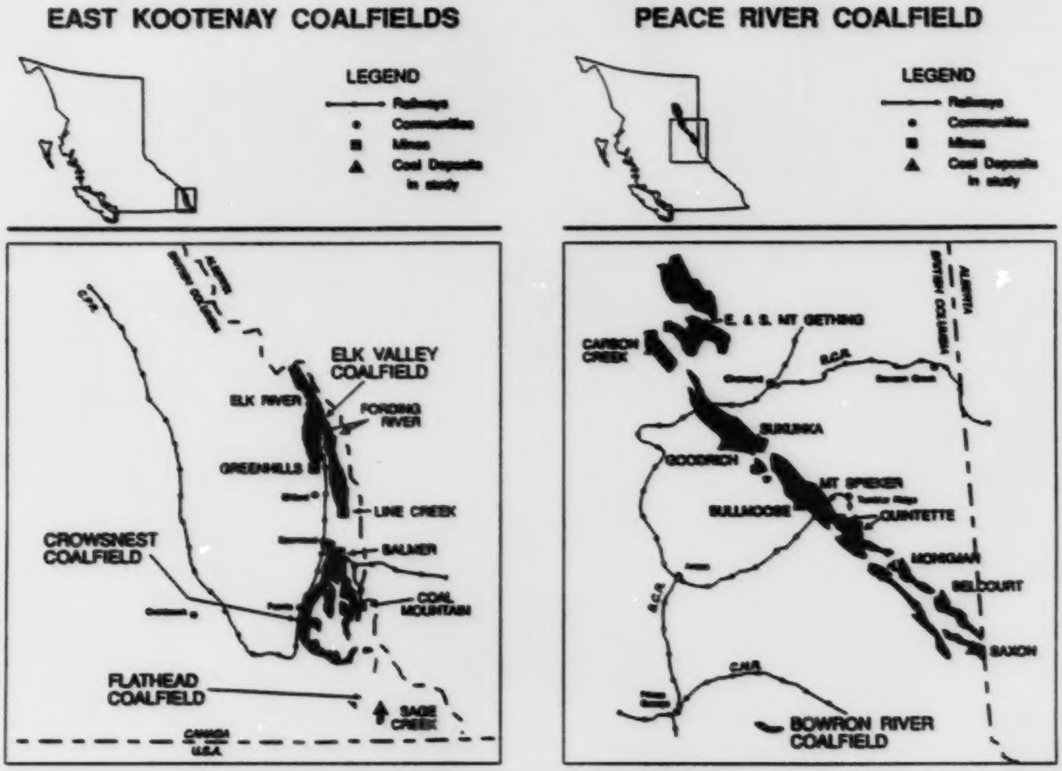
EAST KOOTENAY COALFIELDS
LEGEND
Railways
Communities
Mines
Coal Deposits in study
C.P.R.
ALBERTA
BRITISH COLUMBIA
ELK VALLEY COALFIELD
ELK RIVER
FORDING RIVER
GREENHILLS
LINE CREEK
CROWSNEST COALFIELD
BALMER
COAL MOUNTAIN
FLATHEAD COALFIELD
SAGE CREEK
CANADA
U.S.A.
PEACE RIVER COALFIELD
LEGEND
Railways
Communities
Mines
Coal Deposits in study
ALBERTA
BRITISH COLUMBIA
E. & S. MT GETHING
CARBON CREEK
B.C.R.
SUKUNKA
GOODRICH
MT SPIEKER
BULLMOOSE
QUINTETTE
MONKMAN
BELCOURT
SAXON
B.C.R.
C.N.R.
BOWRON RIVER COALFIELD

Figure 1: Locations of coking coal mines and deposits referred to in this study.

DATA COLLECTION

Data used in this paper come from two main sources, assessment reports, written by industry geologists to document exploration results on individual coal properties and deposits, and analysis of a set of channel samples collected by the author at all seven of the mines in the

Peace River and East Kootenay coalfields (Figure 1) in 1989. The former set of data is considered to be the more representative, because it is based on many more readings, while the latter set provides the opportunity to compare phosphorus with other elements and with the mineralogy of low-temperature ash.

ASSESSMENT REPORT DATA

Exploration assessment reports were used to compile databases of phosphorus concentrations in raw and clean coals. In some cases data on both raw and clean fractions of the same sample were available. The exploration properties represented by this data are listed in Table 1 and their locations are shown in Figure 1. Ash and sulphur data were also collected for each record. Most of the data represent analyses of drill-core samples. In most cases, data were reported as per cent P in coal, although for some properties the P values in coal had to be calculated from the concentration of P_2O_5 in coal ash. Most data were available on an air-dried basis, and those that were not were converted. Data in reports for which the bases of reporting the phosphorus concentration and ash content were different, or where the sample type or basis of reporting were not explicitly defined, were not included.

TABLE 1
COAL DEPOSITS COVERED IN THIS STUDY

REGION	FORMATION	PROPERTY / DEPOSIT NAME	SAMPLE TYPE	No. of SAMPLES	SOURCE OF DATA
Southeast	Mist Mountain	Elk River	raw & clean	51	Assessment report 274
		Elk River	clean	194	Assessment report 276
		Fording River	raw, whole-seam	7	channel sampling program
		Greenhills	raw, whole-seam	6	channel sampling program
		Line Creek, 10A-seam	raw, ply-by-ply	5	channel sampling program
		Line Creek, 10B-seam	raw, ply-by-ply	5	channel sampling program
		Line Creek, 9-seam	raw, ply-by-ply	8	channel sampling program
		Line Creek, 8-seam	raw, ply-by-ply	19	channel sampling program
		Balmer	raw, whole-seam	6	channel sampling program
		Coal Mountain	raw, whole-seam	3	channel sampling program
Northeast	Gething	Carbon Creek & Carbon Creek W.	raw	58	Assessment reports: 504, 507 & 508
		E. Mt. Gething & S. Mt. Gething	raw	11	Assessment reports: 520 & 639
		Goodrich	raw	21	Assessment reports: 532 & 534
		Sukunka	clean	48	Assessment reports: 645 & 650
		Mt. Spieker	clean	15	Assessment reports: 552, 553 & 555
Northeast	Gates	Bullmoose	raw, whole-seam	6	channel sampling program
		Mt. Spieker	clean	38	Assessment reports: 552, 553, 555, 556 & 558
		Quintette	raw & clean	303	Assessment reports: 603, 611, 615 & 619
		Quintette	raw, whole-seam	2	channel sampling program
		Monkman	clean	43	Assessment reports: 543, 545, 546 & 547
		Belcourt	raw & clean	97	Assessment reports: 463 & 466
		Saxon	raw & clean	86	Assessment report 628

SAMPLING

Channel samples were collected from fresh coal faces in active mines (see Figure 1 and Table 1) for trace element analyses, and to provide samples for low-temperature ashing

(Grieve and Holuszko, 1991). The channels were approximately 10 cm wide by 5 cm. Each sample was intended to be representative of a seam or interval. In the cases of six of the seven mines, whole-seam samples were collected, for a total of 30 samples, 22 from southeast B.C. and 8 from northeast B.C. At the other mine, Line Creek, four major seams, 10A, 10B, 9 and 8, were sampled in plies of average 50 cm thickness, for a total of 37 samples.

SAMPLE PREPARATION AND ANALYSIS

Samples were dried, crushed, riffled and screened in accordance with ASTM standard procedures. Proximate and other routine analyses were also carried out using ASTM standard techniques. Phosphorus in coal was determined by ASTM method D2795, and reported as per cent P_2O_5. These values were converted to per cent P in coal. Fluorine in coal was determined by ASTM method D3761.

Representative splits of minus 60-mesh coal were provided to the author for low-temperature ashing. This technique, which uses radio frequency (RF)-generated oxygen plasma, is a routine way of producing an ash with the original minerals essentially preserved (see for example, Miller et al., 1979). The Ministry's plasma asher is an LFE Corporation model LTA-504, which uses an RF power supply that operates at 13.56 Mhz. Five to ten grams of coal is placed in a silica sample boat. One boat is placed in each of the four 10 centimetre-diameter reaction chambers, which are then evacuated using a vacuum pump. Ashing is done using 200 watts total RF power (50 watts per chamber), and a total oxygen bleed-rate of about 30 cubic centimetres per minute. Samples are left exposed to the oxygen plasma round-the-clock, for a total of about 72 hours. They are stirred at least twice a day using a glass rod, in order to bring unreacted coal to the surface. At the end of the reaction time a small amount, less than 1 per cent (estimated) per volume, of unreacted organic material is left in the residue. This is assumed to be made up of inertinite. Low-temperature ashes are ground using an agate mortar and pestle, prior to X-ray diffraction analysis.

DETERMINATION OF ORGANIC/INORGANIC ASSOCIATION IN COAL

The mode of association of a trace element in coal is as important as its actual concentration (Finkelman, 1980). One generally accepted and simple method of gaining a preliminary impression of this factor is to plot the concentration of the element versus the ash content (Nicholls, 1968). If the concentration increases with increasing ash, it can be tentatively concluded that the element is predominantly associated with the inorganic fraction of the coal. Conversely, a constant or decreasing concentration of the element suggests an association with the organic fraction. A further refinement is to divide the concentration of the element in each sample by the ash content of the sample, in effect calculating the element's concentration in ash, and to plot this value against the ash. With this approach, element concentrations which plot on a horizontal line suggest a predominantly inorganic association, while those which plot on a line with negative slope imply organic association. Nicholls (1968) also makes a case for being able to detect a mixed association with this type of graph. An example of the type of plot which might be interpreted in this way is Figure 6f, where there is a high negative slope at low ash contents (supposedly organic association), and no slope over higher ash contents (inorganic). The validity of the assumptions inherent in use of element/ash graphs will be discussed later.

A second widely-used approach for determining an element's affinity is to compare its concentration in specific gravity fractions from sink-and-float testing (Gluskoter et al., 1977). Elements with organic affinity should be concentrated in the light fraction(s), while those with inorganic affinity should be enhanced in the heavy fraction(s). Problems with these assumptions will also be discussed later.

Other available methods, such as SEM-EDX analysis (Van der Flier-Keller and Fyfe, 1987), are not dealt with here because they have not been attempted to date. Future work will utilize other techniques to determine affinities of phosphorus and other trace elements.

TABLE 2
STRATIGRAPHIC VARIATIONS IN PHOSPHORUS
CONCENTRATIONS IN RAW MIST MOUNTAIN FROMATION COALS *
(ELK RIVER PROPERTY)

SEAM	No. of SAMPLES	MEAN P (%)	RANGE IN P (%)
2	2	0.021	0.020 - 0.022
3	3	0.114	0.048 - 0.183
4	4	0.027	0.015 - 0.038
6	1	0.080	-
7	2	0.062	0.057 - 0.066
8	2	0.072	0.058 - 0.085
9	2	0.030	0.028 - 0.031
10	2	0.059	0.045 - 0.073
12	3	0.087	0.072 - 0.109
13	10	0.096	0.047 - 0.152
14	6	0.059	0.039 - 0.078
15	2	0.088	0.079 - 0.096
16	6	0.105	0.058 - 0.151
17	3	0.094	0.084 - 0.113
18	2	0.074	0.073 - 0.075

* Seams listed in ascending stratigraphic order; all data from assessment reports

RESULTS

PHOSPHORUS CONCENTRATIONS IN RAW COALS

Raw Mist Mountain Formation coals (from the East Kootenay coalfields of southeast B.C.) have mean phosphorus concentrations of 0.076 per cent in the case of assessment report data, and 0.096 per cent in the case of the whole-seam channel samples. Variations in P concentration with stratigraphic position for assessment report and channel sample data are shown in Table 2 and Figure 2a, respectively. A general up-section increase in phosphorus contents has been noted at one location in southeast B.C. (B. Ryan, pers. comm., 1988). However, neither of the data sets shown here suggests that there is any systematic variation in phosphorus values with stratigraphic position. Data in Figure 2a suggest that phosphorus contents are lowest near the base and top of the formation, and highest in the middle. This pattern, however, is almost identical to that of the ash contents (Figure 2b). The basal seam (number 2) and one other in the lowermost part of the formation (number 4) on the Elk River property have the lowest phosphorus contents (Table 2), although the amount of data for each seam is very small. It also appears that the upper half of the formation (seams 13 and above) has a higher average phosphorus content than the lower half (0.088 per cent compared with 0.061 per cent), but the reliability of this is questionable. One obvious conclusion to be derived from Table 2 is that there can be a great deal of variation in raw phosphorus concentrations between samples of the same seam.

In the cases of the four seams at Line Creek, numbers 9 and 8 have higher average phosphorus contents than the underlying 10A and 10B-seams from the base of the formation, but there are no consistent in-seam variations (Figures 2c and 2d).

Raw Gething Formation coals (from northeast B.C.) have a mean phosphorus concentration (air dried) of 0.063 per cent; all data are from assessment reports. No stratigraphic trend in phosphorus contents is apparent.

Raw Gates Formation coals (from northeast B.C.) have mean phosphorus concentrations of 0.042 per cent in the case of assessment report data, and an almost identical 0.043 per cent in the case of the whole-seam channel samples. Available data suggest that raw coal phosphorus concentrations tend to be higher in seams in the upper part of the Gates Formation than in the lower, with a general but irregular up-section increase (Table 3). Again, the amount of variation of phosphorus values within data for some individual seams is very striking. The upward trend is basically confirmed by the channel sample data (Figure 2e).

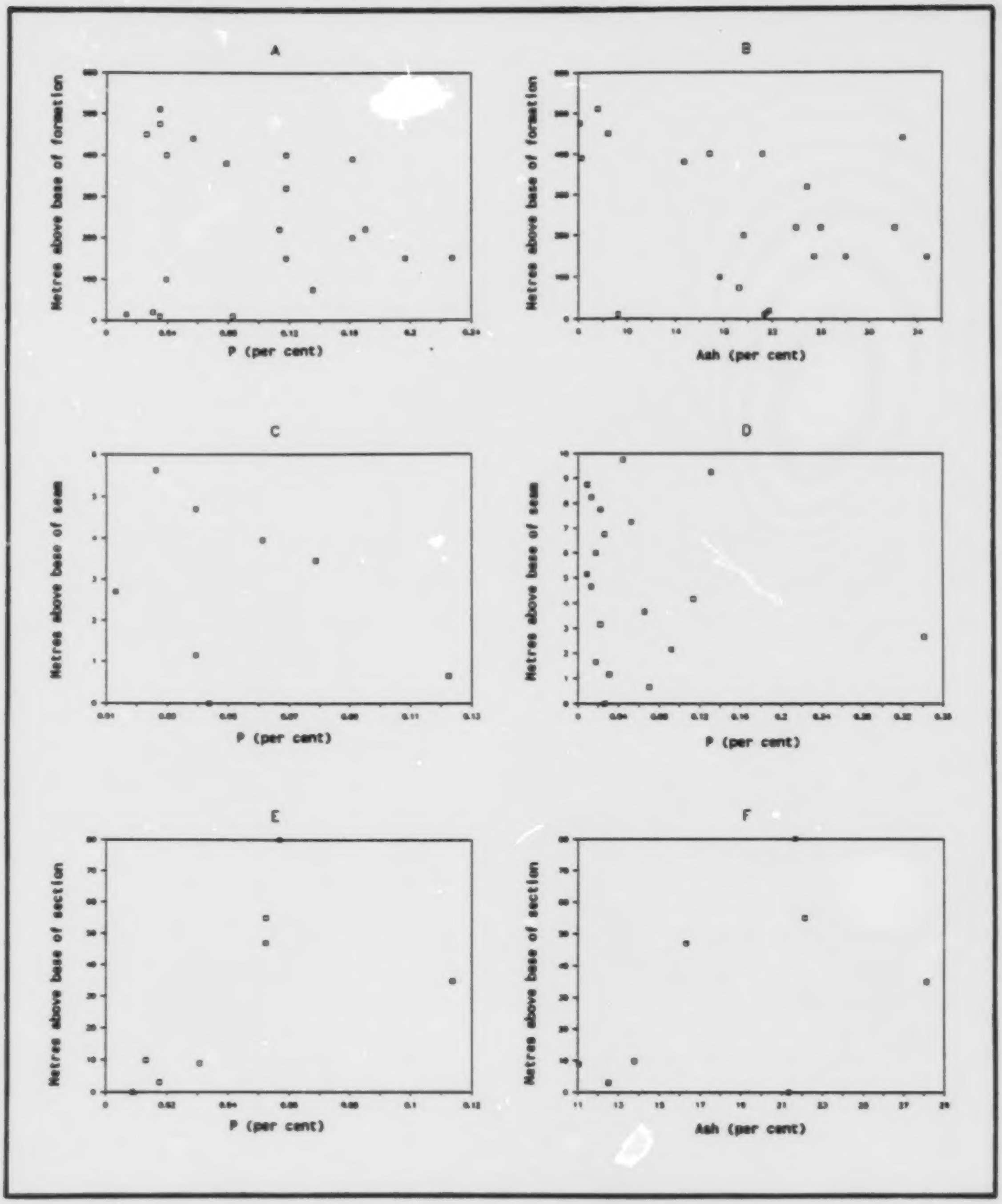

Figure 2: Variations in phosphorus concentrations and ash contents with approximate stratigraphic position, for raw, channel samples collected from active mines. (a) phosphorus, East Kootenay coalfields; (b) ash, East Kootenay coalfields; (c) phosphorus, Line Creek 9-seam; (d) phosphorus, Line Creek 8-seam; (e) phosphorus, Peace River coalfield; (f) ash, Peace River coalfield.

As was the case with the Mist Mountain channel samples, however, the stratigraphic profile of phosphorus values matches fairly closely the profile of ash contents in the samples (Figure 2f).

TABLE 3
STATIGRAPHIC VARIATIONS IN PHOSPHORUS
CONCENTRATIONS IN RAW GATES FORMATION COALS *

PROPERTY	SEAM	No. of SAMPES	MEAN P (%)	RANGE IN P (%)
Belcourt	1	18	0.028	0.009 - 0.051
	2	14	0.026	0.011 - 0.064
	3	4	0.029	0.018 - 0.052
	4	5	0.014	0.008 - 0.022
	5	11	0.025	0.007 - 0.047
	6	20	0.063	0.004 - 0.224
	7	9	0.042	0.002 - 0.146
	8	16	0.052	0.020 - 0.124
Saxon	1	27	0.014	0.002 - 0.044
	2	18	0.019	0.006 - 0.035
	3	10	0.025	0.006 - 0.079
	4	25	0.021	0.005 - 0.049
	5	3	0.020	0.010 - 0.033
	10	2	0.043	0.031 - 0.064

* Seams listed in ascending stratigraphic order; all data from assessment reports

STATISTICAL RELATIONSHIPS BETWEEN PHOSPHORUS AND ASH

Correlation coefficients (r) between phosphorus and ash contents in raw B.C. coking coals are listed in Table 4. Graphs demonstrating some examples of these relationships, along with corresponding relationships between phosphorus in ash versus ash, are shown in Figures 3 to 7. In the case of the assessment report data, r values are low and there are very few instances where there is significant correlation between P and ash content (Table 4). F and K-seams at Quintette, however, do show a significant positive correlation at the 99 per cent confidence level (Figure 7a), while the Gates Formation as a whole (Figure 5a), along with the Gething Formation (Figure 4a), shows a significant relationship at the 95 per cent level, although the r values are not high. In the case of the channel sample data, both the Gates and Mist Mountain formations show a significant correlation at the 95 per cent confidence level (Table 4; Figures 3c and 5c). This is consistent with the similarity between the stratigraphic profiles of phosphorus and ash in the channel sample data set (Figure 2) noted above.

Consistent with the general lack of strong correlations, interpretation of the plots of phosphorus versus ash (Figures 3 to 7) is not straightforward. There is a large amount of data scatter in nearly all cases, and few examples which allow application of Nicholl's (1968) general principles of element affinity (see above). Some of the graphs of phosphorus in ash versus ash, however, appear to

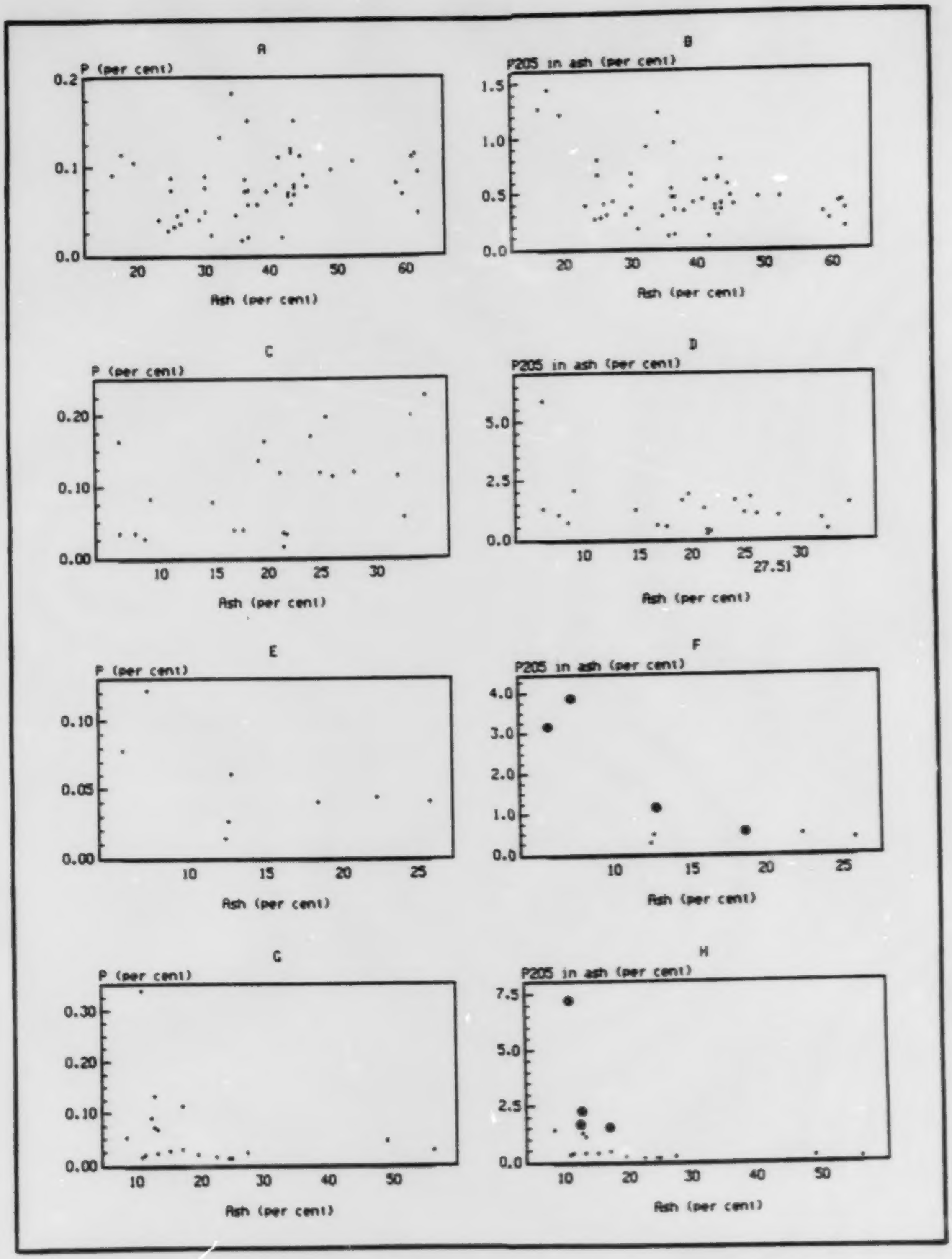

Figure 3: Variations in phosphorus concentration with ash content, raw coals, Mist Mountain Formation, East Kootenay coalfields. (a) and (b): assessment report data; (c) and (d): whole-seam channel samples; (e) and (f): Line Creek 9-seam ply-by-ply channel samples; (g) and (h): Line Creek 8-seam ply-by-ply channel samples. Large dots in (f) and (h) represent samples in which fluorapatite was positively identified in greater than trace amounts in low-temperature ash.

TABLE 4
CORRELATION COEFFICIENTS AND LEVELS OF SIGNIFICANCE BETWEEN P AND ASH IN RAW COALS

REGION/ FORMATION	PROPERTIES/DEPOSITS REPRESENTED	DATA SOURCE	r	95% CONFIDENCE	99% CONFIDENCE	No. of SAMPLES
Southeast	Elk River	Assessment report	0.205	no	no	51
Southeast	Fording, Greenhills, Balmer, Coal Mtn.	Channel samples	0.412	yes	no	22
Southeast	Line Creek 8-seam ply-by-ply	Channel samples	-0.288	no	no	19
Northeast/Gething	Carbon Creek, Mt. Gething, Goodrich	Assessment reports	0.239	yes	no	88
Northeast/Gates	Quintette, Belcourt, Saxon	Assessment reports	0.104	yes	no	486
Northeast/Gates	Quintette	Assessment reports	0.109	no	no	303
Northeast/Gates	Quintette K-seam	Assessment reports	0.666	yes	yes	32
Northeast/Gates	Quintette J-seam	Assessment reports	0.116	no	no	69
Northeast/Gates	Quintette I-seam	Assessment reports	-0.138	no	no	25
Northeast/Gates	Quintette G-seam	Assessment reports	0.117	no	no	31
Northeast/Gates	Quintette F-seam	Assessment reports	0.463	yes	yes	52
Northeast/Gates	Quintette E-seam	Assessment reports	-0.233	no	no	49
Northeast/Gates	Quintette D-seam	Assessment reports	0.107	no	no	40
Northeast/Gates	Belcourt	Assessment reports	-0.024	no	no	97
Northeast/Gates	Saxon	Assessment reports	0.149	no	no	86
Northeast/Gates	Quintette and Bullmoose	Channel samples	0.730	yes	no	8

be similar to the graphs which supposedly demonstrate both organic and inorganic association. For examples, see Line Creek 8-seam (Figure 3h), Gething Formation in total (4b), Gates Formation in total (Figure 5b), Quintette, Belcourt and Saxon properties (Figures 6b, d and f), Quintette F-seam (7b), Belcourt 8-seam (7d) and Saxon 1-seam (7f). These graphs all display a high negative slope at low ash concentrations (the "organic" component), and a zero slope at higher ash levels ("inorganic"). Comments concerning the validity of this interpretation are included under "Discussion."

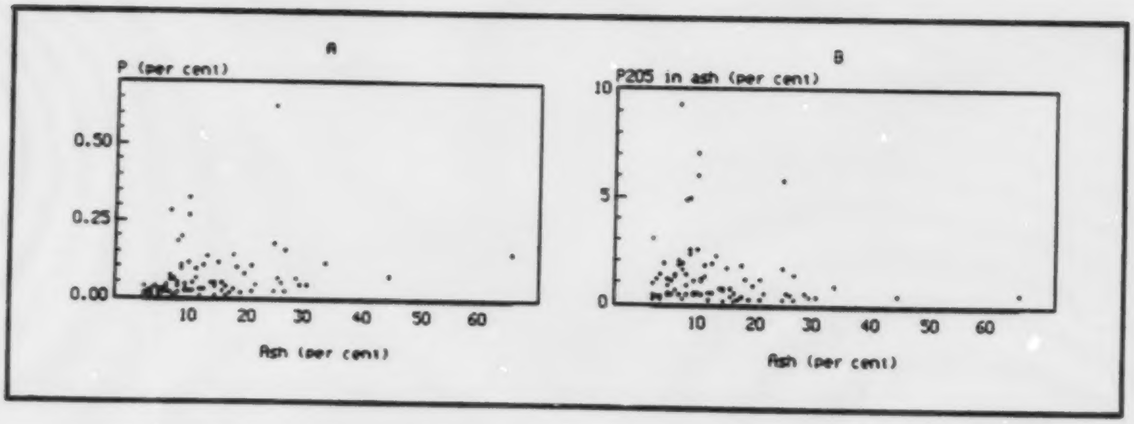

Figure 4: Variations in phosphorus concentration with ash content, raw coals, Gething Formation, Peace River coalfield. All data are from assessment reports.

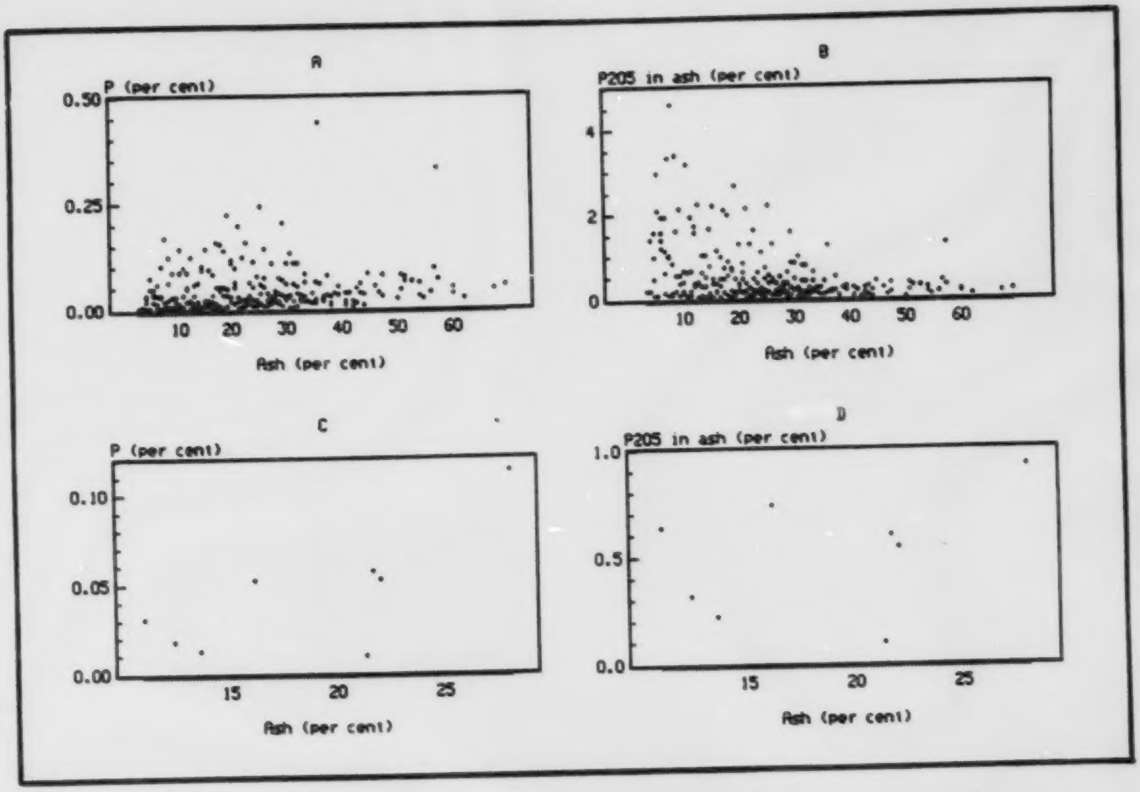

Figure 5: Variations in phosphorus concentration with ash content, raw coals, Gates Formation, Peace River coalfield. (a) and (b): assessment report data; (c) and (d): whole-seam channel samples.

LOW-TEMPERATURE ASH MINERALOGY OF RAW COALS

The suites of minerals in low-temperature ash derived from the channel samples are listed in Grieve and Holuszko (1991). Quartz, kaolinite, illite and carbonates, in order of decreasing abundance, are generally the most common minerals in raw B.C. coking coals. Of interest to this study is the presence of accessory apatite and fluorapatite in many of the samples. Samples in which fluorapatite was positively identified in greater than trace amounts are highlighted in Figures 3f and 3h. On average, apatite minerals are more common in Mist Mountain Formation coal samples than in Gates Formation coals, although the number of Gates samples is very small. Seams in the lowermost part of the Mist Mountain Formation, in particular 10A and 10B-seams from Line Creek, the Mammoth seam from Coal Mountain, and 5-seam from Fording, contain no detectable apatite. The phosphate mineral gorceixite, a member of the crandallite series, was tentatively identified in the low-temperature ash of one Fording River sample.

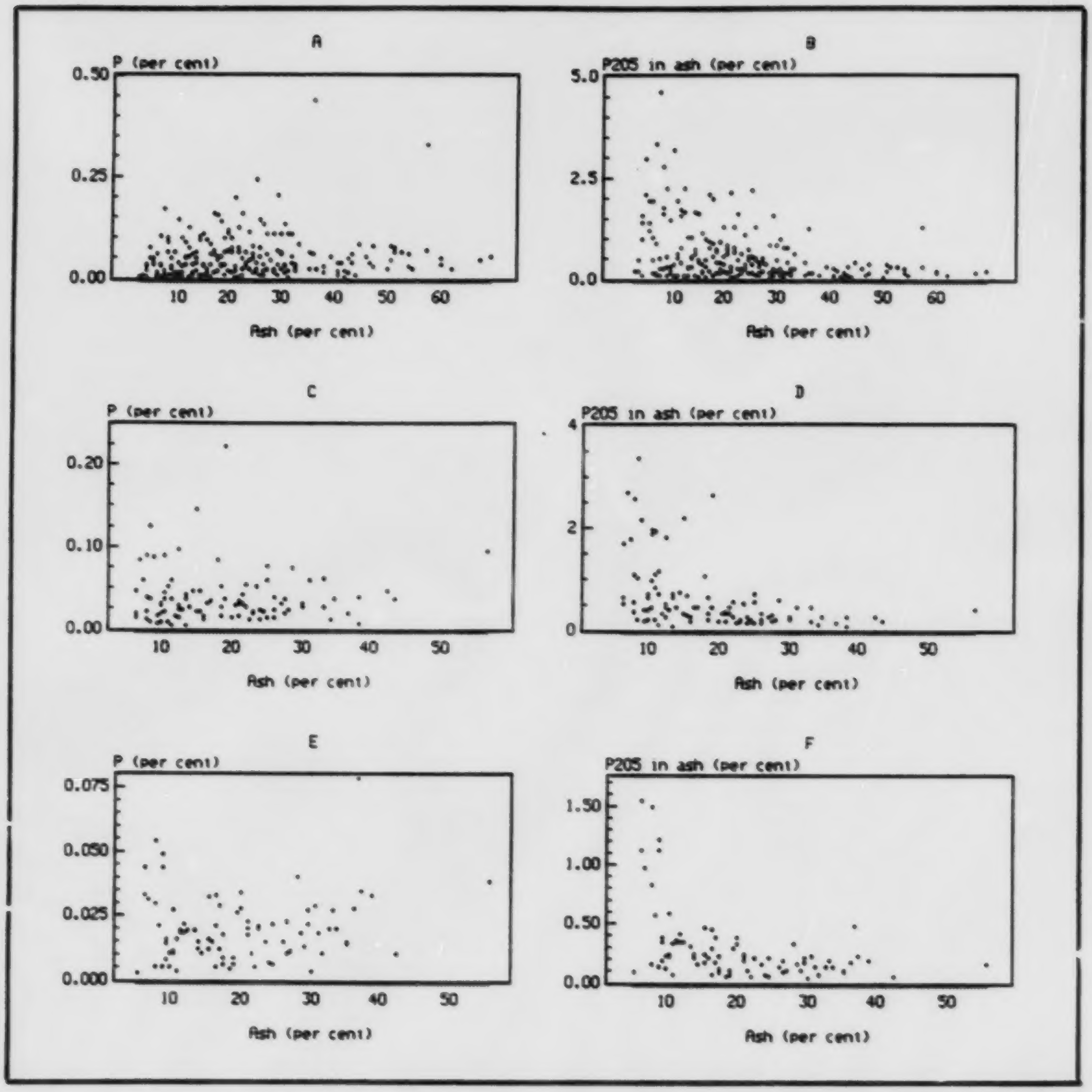

Figure 6: Variations in phosphorus concentration with ash content, raw coals, Gates Formation, Peace River coalfield. All data are from assessment reports, and represent subsets of data in Figures 7a and 7b. (a) and (b): Quintette; (c) and (d): Belcourt; (e) and (f): Saxon.

RELATIONSHIPS BETWEEN PHOSPHORUS AND FLUORINE

The concentration of the trace element fluorine in the channel samples was also determined. A positive correlation between phosphorus and fluorine would be expected if a significant fraction of the phosphorus occurs in fluorapatite. Figure 8 displays P versus F plots; the two elements are positively correlated at the 99 per cent confidence level in all examples shown, except for the Gates Formation samples (Figure 8d), for which the confidence

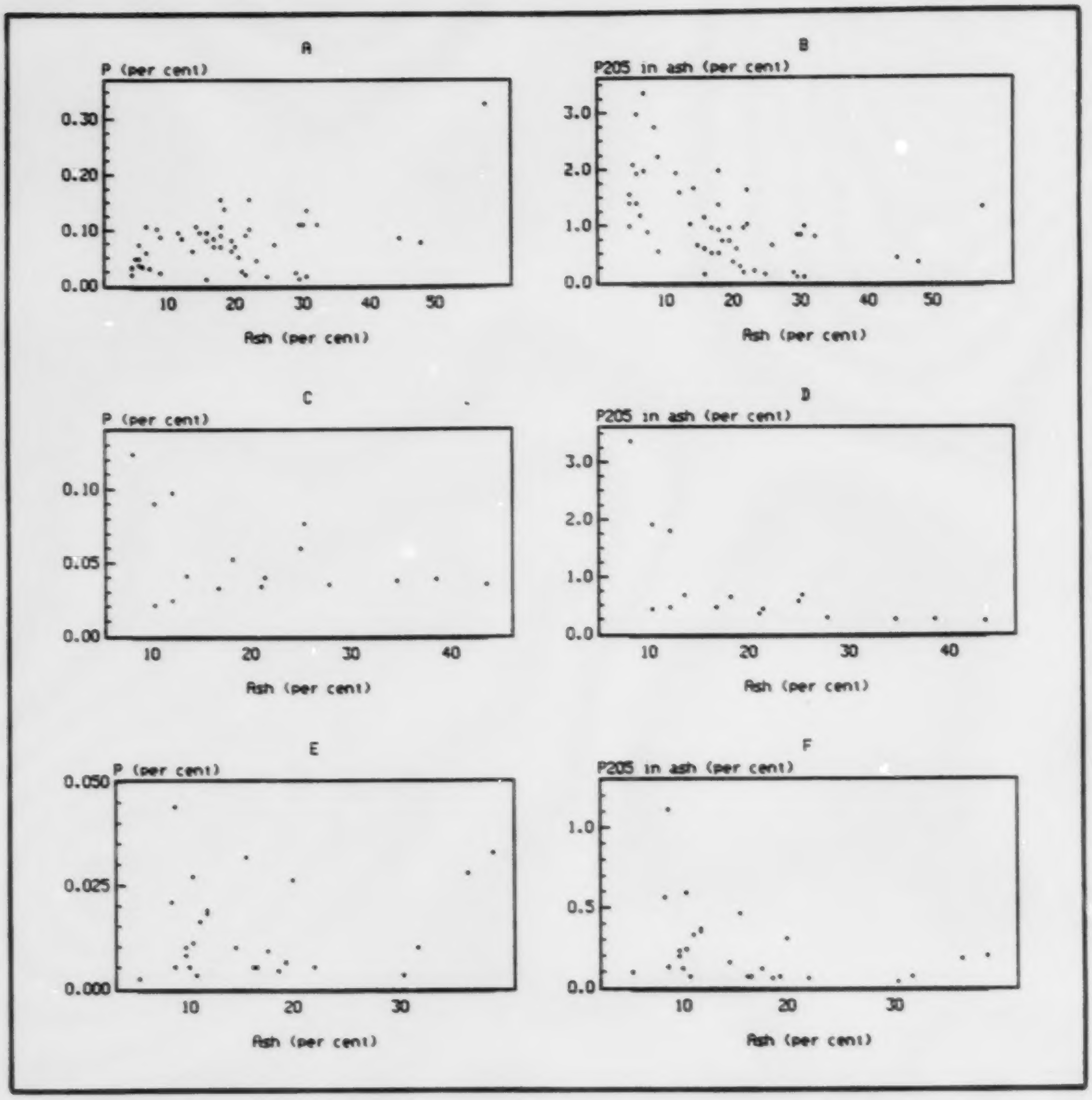

Figure 7: Variations in phosphorus concentration with ash content, raw coals, Gates Formation, Peace River coalfield. All data are from assessment reports, and represent subsets of data in Figure 7a and 7b. (a) and (b): Quintette F-seam; (c) and (d): Belcourt 8-seam; (e) and (f): Sason 1-seam.

level is 95 per cent. The correlation coefficients (r) are as follows: Mist Mountain Formation (Figure 8a), 0.92; Line Creek 9-seam (8b), 0.88; Line Creek 8-seam (8c), 0.76; Gates Formation (8d), 0.72.

PHOSPHORUS CONCENTRATIONS IN CLEAN COALS

For the Mist Mountain Formation the mean phosphorus concentration in clean coals, based on assessment report

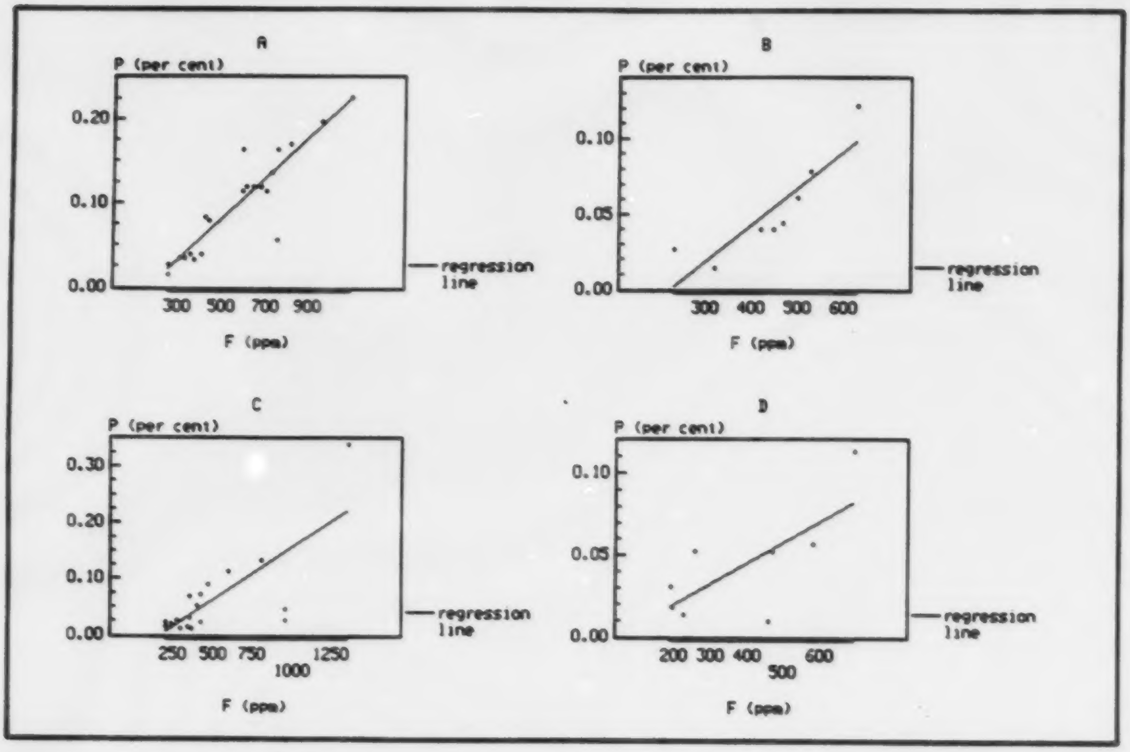

Figure 8: Variations in phosphorus with fluorine concentrations, based on raw channel samples. (a): East Kootenay coalfields, whole-seam samples (Mist Mountain Formation); (b): Line Creek 9-seam, ply-by-ply samples (Mist Mountain Formation); (c): Line Creek 8-seam, ply-by-ply samples; (d): Peace River coalfield, whole-seam samples (Gates Formation).

data, is 0.033 per cent, while the mean phosphorus concentration in clean Gething Formation coals is 0.030, and in clean Gates Formation coals the value is 0.044 per cent. In the last case, the value is essentially unchanged from the raw coal value, while for the other two the concentration in clean coals represents a lower value than that in raw coals. This comparison is midleading, however, because of differences in analytical procedures between different exploration companies (see next paragraph and "Discussion").

In certain cases, clean and raw phosphorus values were available for the same set of samples. Where this occurs a new variable, delta P, was derived for each sample, by subtracting the raw P concentration from the clean value. Delta P values between -0.01 and +0.01 per cent were interpreted as representing no change, as the error in each reading is assumed to be ±0.005 per cent. For the Mist Mountain Formation, phosphorus concentration decreased (that is, delta $P<-0.01$) when the coal was washed in 39 out of 51 samples, and increased in only 2 cases. For the Gates

Formation the situation is somewhat different, with the majority of samples, 285 out of a total of 486, experiencing no change, 79 samples showing a decrease in phosphorus after washing, and 59 exhibiting an increase. The large volume of Gates Formation data also permits some seam-by-seam comparisons. In most seams more than 70 per cent of the samples exhibit no change, that is, delta P is between -0.01 and +0.01. However, there is one example where 20 out of 49 samples experienced an increase (delta P>+0.01) and only 5 underwent a decrease. In the immediately underlying seam 17 out of 52 samples exhibit a decrease and only one experienced an increase. Even in these two relatively extreme examples, however, a high percentage of the samples showed no change. It is difficult to make conclusions based on this contrast between the Mist Mountain and Gates coals, primarily because most of the Gates samples were crushed to a coarser maximum size and were floated in higher specific gravity media than the Mist Mountain coals. This would tend to hinder liberation and separation of mineral matter in the Gates samples.

DISCUSSION

The range in P values in metallurgical coal products from B.C. is 0.023 to 0.079 per cent, with an unweighted average of 0.046 per cent (figures derived from data in Price and Gransden, 1987). The calculated means of clean coal phosphorus data in this study are very close to this average, and in the case of the Gates Formation the mean corresponds almost exactly. Overall, a phosphorus concentration on the order of 0.05 per cent is a representative average for our clean coking coals. With raw coals it is not possible to determine a single average, but mean phosphorus contents in the three metallurgical coal-bearing formations range from about 0.04 to 0.08 per cent.

The estimated range of phosphorus contents in most world coals is on the order of 0.001 to 0.3 per cent (Swaine, 1990), and an estimated world-wide average is 0.05 per cent (Bertine and Goldberg, 1971). The mean concentrations of phosphorus in British Columbia's coking coals, clean and raw, clearly compare favourably with both this range and average. Moreover, phosphorus contents in B.C. coals do not appear to be anomalous when compared with ranges of values of coals from Australia, South Africa, Europe, USA, UK and other regions (see Swaine, 1990, Table 5.23). Phosphorus concentrations in 200 samples of Bowen Basin (Queensland) coal, for example, range from 0.001 to 0.35 per cent. When comparing the mean concentrations in our coals with mean values from other countries some contrasts are observed. For example, coals from the eastern US, including Appalachian coals cited by Finkelman (1980), for which the mean in 754 raw(?) samples is 0.018 per cent, tend to contain less phosphorus than our coals. The average phosphorus content in UK coals is 0.025 per cent (British Coal Corporation, unpublished data, in Burchill et al., 1990), while the average phosphorus concentration in coals from New South Wales and Queensland is 0.031 per cent (Swaine, 1977).

Raw Mist Mountain Formation (southeast B.C.) coals have slightly higher mean phosphorus concentrations than the Gething Formation coals (northeast B.C.), which in turn contain more than the Gates Formation (also northeast B.C.). There is no systematic variation in phosphorus concentrations with stratigraphic position in the Mist Mountain Formation, although the lower half of the formation appears, on average, to contain less phosphorus than the upper half. The degree of variability in phosphorus concentrations within individual seams is pronounced. One trend noted, however, is that the base of the formation appears to contain coals relatively depleted in phosphorus; this is consistent with the lack of detection of phosphate minerals in seams at this stratigraphic position. In the case of the Gates Formation coals, a general up-section increase in phosphorus contents is noted, but data are again highly variable.

One interesting result, obtained from the channel sample data, is that for both the Mist Mountain and Gates formations variations in phosphorus with stratigraphic position are similar to variations in the ash contents of the samples. This suggests that any effect of stratigraphic position on phosphorus contents can be overridden by the influence of variations in the ash content of individual samples.

This in turn raises the question of the form(s) of association of phosphorus in our coals. Phosphorus in coals, especially higher-rank coals, is generally believed to be associated predominantly with inorganic material (Burchill et al., 1990), although a small but uncertain proportion may be associated with the organic fraction (Swaine, 1990; Finkelman, 1980). The phosphorus-containing mineral phases in coals include apatite, most commonly fluorapatite (Swaine, 1977), crandallite-series minerals, monazite and xenotime (Finkelman, 1980). Several recent studies (e.g., Finkelman, 1980; Lyons et al., 1990) have stressed the relative importance of very small (micron and submicron-sized) accessory mineral grains, including phosphates, dispersed throughout the organic matrix as sites for trace elements in coal.

Four types of evidence have been applied in this study to determine the mode of occurrence of phosphorus in B.C. coking coals: comparison and correlation with ash content, low-temperature ash mineralogy, correlation with fluorine concentration, and comparison of phosphorus concentration in clean and raw coals.

The graphs showing phosphorus in coal versus ash and phosphorus in ash versus ash (Figures 3 to 7), as mentioned earlier, can not be interpreted with certainty. As noted, however, some of the latter type of graph appear to have two distinct components, a line with a high negative slope at low ash contents, and a horizontal line at higher ash contents. This type of relationship has been noted elsewhere (Nicholls, 1968; Finkelman, 1980), and has, in some cases, been interpreted to represent two types of association, organic association in the low-ash range, and inorganic otherwise. As pointed out by Nicholls (1968), it is most appropriate to study element associations using data from one seam and preferably from one location, as is the case with the Line Creek samples here. Based on data for 8 and 9-seams (Figures 3f and 3h), it is apparent that the samples for which accessory fluorapatite was identified in greater than trace amounts, are among those low-ash samples which form the portion of the relationship with the high negative slope, that is, the portion which would be attributed to organic association using Nicholls' (1968) approach. If all these samples were removed from Figures 3f and 3h, the remaining data would plot on horizontal lines, the relationship indicative of inorganic association.

These examples demonstrate clearly that another critical variable needs to be considered in interpreting graphs like those in Figures 3 to 7, and that is the mineralogy of the inorganic fraction. As noted by Finkelman (1980), the presence of a very small amount of an accessory mineral containing a trace element, in this case apatite, is capable of producing a significant increase in the concentration of that element, with only a negligible increase in ash content. This effect appears to be showing up in the low-ash samples of Line Creek 8-seam and 9-seam studied here, and presumably in other instances where this type of two-component graph occurs (for example, Figure 6f). This verifies that the main weakness of this approach is that it assumes that the trace element (phosphorus) concentration in each fraction or increment remains constant (Nicholls, 1968; Finkelman, 1980). Apparently the influence of this type of variability is greatest at low-ash levels.

These data therefore suggest that phosphorus in B.C. coking coals is associated with the inorganic fraction, primarily with apatite minerals, including fluorapatite. One test of this conclusion is to look at the relationships between phosphorus and fluorine (Figure 8); strong positive correlations would confirm a fluorapatite association. The correlations are, in fact, highly significant, particularly for southeast B.C. samples.

The comparisons between phosphorus contents in raw and clean samples of Mist Mountain coals also tend to confirm an inorganic association. For example, the mean phosphorus concentration in clean coal is substantially lower than the mean in raw coals. Moreover, where phosphorus values are available on both raw and clean coal from the same samples, the majority of clean Mist Mountain coals contain less phosphorus than corresponding raw coals.

In the case of the Gething Formation, it was not possible to compare raw and clean coal from the same sample, but the substantially lower mean phosphorus concentration in clean coals, compared to raw coals, suggests an inorganic association.

With the Gates Formation the situation appears to be different - the overall mean phosphorus concentration in clean coals is essentially the same as that in raw coals, and there is a higher proportion of samples for which separation of phosphorus is not achieved during washing, or for which phosphorus concentrations actually increased. Despite this, there is no valid basis for concluding that the association of phosphorus in Gates coals is fundamentally different. As mentioned previously, the analytical conditions most commonly used for the Gates samples would tend to liberate and separate relatively less mineral matter than the conditions applied with the coals from the other formations. Moreover, the relationships between phosphorus and ash, and between phosphorus and fluorine, are similar to those derived from the Mist Mountain Formation data, suggesting that the phosphorus in the Gates Formation coals is associated in essentially the same manner. These results also do not suggest that the Gates Formation coals are any less amenable to upgrading with respect to phosphorus contents.

Even if a direct comparison between washability results for the Mist Mountain and Gates samples were valid, there are still conditions which could lead to differences in trace element behaviour of the type seen here. Finkelman (1980) and Swaine (1990) have summarized the weaknesses in the washability approach to determining an element's affinity in coal, in particular noting that elements associated with finely dispersed mineral grains will behave as though they are associated with the organic fraction. Thus an element which appears to be organically associated, or to have a combined organic-inorganic association, may in fact be predominantly inorganically associated.

The crandallite-series mineral gorceixite, which was identified in the low-temperature ash of one Mist Mountian Formation sample, occurs in some tonsteins found in southeast B.C., as does apatite, though less frequently.

This suggests a possible volcanic source for some of the phosphorus in British Columbia coking coals (Goodarzi et al., 1990).

Whether phosphorus represents a negative factor in the marketing of our coking coals depends on many other variables, including the type of iron ore being smelted. The large volume of B.C. coking coal currently being sold on the world market suggests it is not in general a significant problem. Specific users may have more stringent specification requirements, however, and achieving success in these markets may involve tight production control. The data summarized here suggest that, where limiting phosphorus in coal is a concern, it may be necessary to mine seams selectively, and that careful quality control sampling, even within a single seam, may be necessary, to overcome the wide variabilities in phosphorus concentrations. Further work is needed to determine accurately the actual sites within the coal that phosphorus occupies, but this will lead to a better understanding of how to control this element in B.C.'s coking coal products.

CONCLUSIONS

Calculated mean phosphorus concentrations in raw coals of the Mist Mountain, Gething and Gates formations are 0.076 per cent, 0.063 per cent and 0.042 per cent, respectively. There is no consistent stratigraphic trend in mean phosphorus concentrations in the Mist Mountain Formation, but seams in the upper half appear to contain, on average, more phosphorus than those from the lower half, and seams in the basal part of the formation are relatively depleted in phosphorus. In the Gates Formation there appears to be a general up-section increase in the mean concentrations of phosphorus. In all examples studied, variation in raw phosphorus concentrations within samples from a single seam can be large.

Phosphorus in B.C. coking coals is predominantly associated with inorganic material, chiefly apatite minerals, including fluorapatite. The two main factors affecting the phosphorus content of a given coal are the amount of ash and the mineralogy of the accessory minerals.

A representative average phosphorus content in clean B.C. coking coals is 0.05 per cent.

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RELATIONSHIPS BETWEEN COAL QUALITY PARAMETERS IN BRITISH COLUMBIA COALS

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British Columbia coal quality data are being compiled on a region-by-region basis, in order to delineate and understand coal quality characteristics of our coals, and how these coal attributes influence utilization potential. Pre-existing data in industry assessment reports, mainly from drill-core samples, are being supplemented by analyses of raw coal samples collected annually at active coal mines. For this poster, relationships between various pairs of quality parameters have been generated, for example: (a) maximum *vs*. random reflectance; (b) vitrinite reflectance *vs*. (i) volatile matter, (ii) carbon, (iii) hydrogen, (iv) hydrogen/carbon ratio, (v) oxygen, (vi) oxygen/carbon ratio, and (vii) fluidity and dilatometry parameters; and (c) calorific value *vs*. ash.

The linear correlation between mean maximum (R_{max}) and mean random vitrinite reflectance (R_m) is extremely strong (r=0.997), and allows ready conversion from one to the other for B.C.'s bituminous coals. The relationship is:

$$R_{max} = -0.0632 + 1.107 R_m.$$

Application of this relationship to the R_m boundaries corresponding to the upper and lower limits of ASTM rank category medium-volatile bituminous, as defined recently by Cameron (1989) for Western Canadian coals, yields R_{max} boundaries of 0.99 and 1.54 per cent.

Volatile matter (*daf*), hydrogen/carbon ratio, hydrogen (*daf*), oxygen (*daf*) and oxygen/carbon ratio are negatively correlated, in order of decreasing significance, with vitrinite reflectance at the 99 per cent confidence level, while carbon (*daf*) is positively correlated at the same confidence level. The Geiseler fluidity temperatures of initial softening, maximum fluidity and resolidification are positively correlated with rank at the 99 per cent level. Maximum fluidity and fluid temperature range are negatively correlated but only at the 95 per cent level in the latter case. Dilatation parameters are not correlated with vitrinite reflectance.

Within individual B.C. coalfields and deposits ash is overwhelmingly the single most important factor controlling calorific value (*air-dried* or *dry*). At an arbitrary ash level of 15 per cent, predicted calorific values on raw B.C. coals are as follows: Hat Creek (lignite) - 25.33 MJ/kg (*dry*); Telkwa (high-volatile A) - 28.59 (*ad*); Klappan (anthracite) - 29.09 (*ad*); East Kootenay (high-volatile A to low-volatile) - 29.23 (*dry*); Gething Formation, Peace River (high-volatile A to low-volatile) - 29.01 (*ad*); and Gates Formation, Peace River (high-volatile A to low-volatile) - 30.09 (*ad*).

Reference

Cameron, A.R. (1989): Relationships of petrographic and chemical parameters in coal rank evaluation for western Canadian coals; *in* Advances in Western Canadian Coal Geoscience, *Alberta Research Council*, Information Series No. 103, pages 225-232.

NOTES

GIS AND THREE-DIMENSIONAL CAD APPLIED TO COMPUTER-MODELLING OF COALFIELDS

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Through its National Coal Inventory, the Geological Survey of Canada has developed extensive databases of surface and subsurface geological data from coalfields across Canada. These data are utilized to create geological models of coalfields to asses contained coal resources in environmental, economic and technological terms; and to provide predictions of geological hazards and complexities to coal mine operators.

The process of developing a geological computer model for a coalfield involves the following steps: 1) manual compilation and interpretation of lithological and other geological data from a variety of hardcopy formats; 2) data entry/verification within data capture/reporting system which utilizes the ORACLE and IMAGE DBMS software; 3) correlation of coal seams, faults and other geological features between data points; 4) extension of correlated geological surfaces to the nodes of a regular grid using various commercial contouring packages; 5) assembly of all surfaces into finished model utilizing inhouse developed software. Once a model which accurately defines the configuration of all correlated surfaces is established, a variety of other models can be created, including lithological models which define the distribution of coal and non-coal lithologies between and within coal zones, and resource models, which define the quality and economic characteristics of the coal seams.

The products of these models include a large number of gridded data sets describing all aspects of coalfield geology and resource potential, as well as various point and vector datasets. These datasets are downloaded to a microcomputer-based GIS (Tydac SPANS), where they are integrated with surface land capability and coal ownership information, and with remotely sensed imagery including Landsat-TM, airborne SAR and scanned aerial photography. The display, modelling and reporting capabilities of the GIS provide a powerful platform for downstream users to utilize the computer models. A three-dimensional CAD system (AUTOCAD) is also utilized both for its display capabilities and as a graphical user interface during the model construction process. Interfaces have been developed which allow the importation of raster, point and vector datasets from the model into the CAD system, creating a three-dimensional drawing which allows viewing of all primary and derived geological elements from any orientation. The CAD system thus provides a powerful capability for visualizing complex data relationships, and for displaying these relationships in hardcopy form. Routes have also been developed from both the GIS and CAD systems to high resolution output devices (SCITEX, FIRE, OPTRONICS) for the automated production of color separations for publication.

NOTES

PINE VALLEY MAPPING AND COMPILATON PROJECT

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This study is a part of the ongoing Peace River Coalfield Digital Mapping Project. Computer-based methods enabled data to be compiled and interpreted efficiently, both in the office and in the field. Base maps with contour, cadastral, drainage and cultural data were obtained in digital form from TRIM files. Software was written (1) to integrate these data, outcrop data, and data from various industry and government sources, and (2) to interface the integrated data with various database, graphical, and structural packages.

The map area is underlain by rocks ranging in age from Triassic and Jurassic in the southwest to Cretaceous in the northeast. Marine clastics make up the Jurassic Fernie Formation and Lower Cretaceous Minnes Group. Alternating marine to non-marine clastics and marine shales of the Bullhead and Fort St. John Groups and the Dunvegan Formation dominate the rest of the Cretaceous.

The map area lies in the Rocky Mountains Foothills, which are divisible into inner and outer belts. Deformation in the inner foothills is characterized by tight, high amplitude folds. The outer Foothills exhibit low amplitude, long wavelength, easily mapped folds. Evidence for blind thrusts and east-dipping faults indicate the possible existence of a triangle zone in the outermost foothills.

Coal seams up to three metres thick and one metre thick are found in the Gething and Bickford Formations, respectively. Thin seams less than one metre thick occur in the Dunvegan, Goodrich and Cadomin Formations. Although economic coal seams exist in the Gates Formation to the south at Bullmoose and Quintette mines, no significant coal was observed in the map area. Vitrinite reflectances from coal samples suggest that this area has potential for coalbed methane exploration.

NOTES

GEOLOGY OF THE QUINSAM COALFIELD

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This paper presents the results of work in the Quinsam coalfield, which is part of the Comox sub-basin. There are two coal deposits of interest in the Quinsam coalfield, Quinsam to the north and Chute Creek to the south.

The Quinsam and Chute Creek coal deposits occur in the Comox Formation, at the base of the Upper Cretaceous Nanaimo Group. The stratigraphy of the Comox Formation resembles that seen in adjoining areas, and three members may be distinguished: in ascending order, Benson, Cumberland and Dunsmuir. Patterns of sedimentation, and hence of coal distribution, were controlled by the irregular topography of the pre-Cretaceous basement. Coal-measures are generally only gently deformed by block-faulting and tilting, with regional dips from 8 to 12 degrees to the northeast. Three sets of faults have been mapped in the study area.

Potentially-mineable coal beds at Quinsam and Chute Creek lie at different positions in the stratigraphic section. In the Quinsam area, these coals are close to basement, in the Cumberland member, and are older than those of the Chute Creek area, which lie near the top of the Comox Formation, in the Dunsmuir member. Coal-measures of the Cumberland member were likely deposited in back-swamps, while the Dunsmuir coals were formed in back-barrier lagoons.

The Quinsam coals can be correlated, with varying assurance, with coals in other parts of the Comox sub-basin. Given available data, the Chute Creek coals cannot be correlated with coals from outside the study area.

The Quinsam and Chute Creek coals straddle the boundary between high volatile 'A' and 'B' bituminous rank. Mean-maximum vitrinite reflectance (Rmax) values range from .52 to .85 per cent. Averaged proximate analysis (air-dried, raw coals) range as follows: residual moisture, 1.8 to 4.0 per cent; ash, 7 to 38 per cent; volatile matter, 27 to 40 per cent; fixed carbon, 34 to 54 per cent, and sulphur, .5 to 4.2 per cent.

The Brinco Coal Corporation is currently operating both open-pit and underground mining operations at the Quinsam mine-site. These export coals average 26.5 megajoules per kilogram (11400 British thermal units per pound), 0.8 per cent sulphur, 36 per cent volatiles, and 48 per cent fixed carbon. Ash content ranges from 9 per cent in open-pit operations to 17 per cent in underground operations.

The current total coal resource estimate for the Quinsam property is 23 300 000 tonnes of open pit reserves and 19 900 000 tonnes of underground reserves, for a total of 43 200 000 tonnes, of which 23 400 000 tonnes are proven. The total in-situ coal resource within the Chute Creek 'A', 'B', 'C' and 'D' coal beds, is 5 260 000 tonnes. Of this resource, 3 350 000 tonnes are considered to be potentially mineable.

Preliminary calculations suggest a potential coalbed methane resource of 30.1 billion cubic metres or .09 trillion cubic feet in the Quinsam sub-basin. This deserves consideration both as a possible on-site energy source and as a potential safety hazard in underground mining operations.

Much of the study area has been intensively drilled, and therefore is unlikely to contain undiscovered coal resources. The country lying east of Iron River and north of Woodhus Creek may contain additional resources in the Chute Creek coal zone and in the No.3 coal bed. The northern limit of mineable coal in the No.1 bed, downdip from Quinsam colliery, is unknown owing to lack of sufficiently deep drilling.

DIGITAL MAPPING- TOOLS

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Digital topographic maps have become available in British Columbia over the last several years. These maps referred to as TRIM (Terrain Resource Inventory Maps) are available at a scale of 1:20 000 for a large part of the province. These digital maps are produced by MAPS-BC. This data is in a format which is readily converted to any of the many CAD or GIS system in common use. In addition, TRIMVIEW, is available at no cost from MAPS-BC, to facilitate viewing of these maps on virtually all IBM compatible computers.

A collection of programs have been produced, TRIM-TOOLS, to allow the user to produce TRIM format maps made of various combinations of the original TRIM map. Simple user supplied data such as bedding orientation symbols, borehole locations and geological contacts can be readily added to the original TRIM base map and viewed on-screen with TRIMVIEW.

Part of the data supplied with a TRIM map is a DEM (digital elevation model) which is simply a collection of elevation points describing the topography of the map area. Typically a DEM will contain over 80 000 points. The availability of this detailed information has facilitated the writing of several programs which increase the accuracy and reduce the time required in dealing with topographic maps during mapping. The first ELEV-GET determines the elevation for any map position. This could be spot elevations or lines such as formation contacts or profile traces. The second program, PHOTO-MAP, allows points and traces on airphotos or any photograph (with know focal length) to be reduced to map coordinates.

NOTES

CONTROLS ON FORMATION OF UPPER CARBONIFEROUS COALS IN THE INTERMONTANE STELLARTON AND CUMBERLAND BASINS OF ATLANTIC CANADA

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ABSTRACT

The Cumberland and Stellarton basins of Nova Scotia are late Carboniferous intermontane basins that formed in a transcurrent setting. The 2500km^2 Athol Syncline area of the Cumberland Basin contains two significant coal-bearing units of Westphalian A-B age, the 1430m thick Joggins Formation and the 600 to 800m thick Springhill Mines Formation. The coals of the Joggins Formation are interbedded with a mixed fluvial and lacustrine assemblage whereas those of the Springhill Mines Formation occur within a predominately fluvial sequence. The coals of the 120km^2 Stellarton Basin are contained within the 2600m thick, predominately lacustrine, Stellarton Formation of late Westphalian B to early D age.

The hydrologically open nature of both basins promoted a stable water table that favoured the development of rheotrophic mires. The position of the basin floor, relative to the water table, was largely controlled by subsidence and sediment supply rates. Higher rates of subsidence, if not balanced by an increase in sediment accumulation, resulted in the floor of each basin being lowered relative to the water table leading to wetter conditions . In the Cumberland Basin sediment accumulation rates generally kept pace with subsidence rates, therefore the basin floor was rarely below the water table for extended periods. In the Stellarton Basin sediment accumulation rates were often not high enough to prevent the basin floor from sinking below the water table. The location and thickness of mires within each basin varied with changes in the sediment accumulation and subsidence rates. When the ratio of sediment accumulation to subsidence was lower in the Cumberland Basin conditions became wetter and mires developed well away from basin margins (e.g. Joggins Formation). When the ratio of sediment accumulation to subsidence became higher, the drier conditions forced mires to develop in areas supplied with groundwater recharge from basin margin alluvial fans (e.g. Springhill Mines Formation). This may imply that the prevailing climate was not sufficiently humid to maintain soley rain-fed peatlands. Basin-wide mires developed in the Stellarton Basin when the ratio of sediment accumulation to subsidence was highest (e.g. Westville and Albion members). When the ratio was lower (Coal Brook and Thorburn members) a perennial lake covered much of the basin floor and mires only formed near basin margins.

The Cumberland Basin was large enough that mires formed even when regional and locally sourced sediment was being carried into the basin. The smaller Stellarton Basin acted as a local base level for regionally sourced drainage systems. Slowing of basin subsidence effectively produced a rise in base level that caused rivers entering the basin to become choked with sediment. It was during these periods that mires could develop within the Stellarton Basin.

INTRODUCTION

Intermontane coal basins vary significantly with respect to size, tectonic history and basin-fill. Generally, however, they are elongate fault basins containing thick non-marine coal-bearing successions with abrupt lateral facies changes and distinct basin margin facies (eg. alluvial fan deposits). The development of paleomires that were the precursors of intermontane coals, can be controlled by a variety of parameters including: climate (Bless *et al.*, 1981; Flores, 1989; Cabrera and Saez, 1987; Calder, 1991); basin hydrology (Flores, *ibid*); subsidence (Bless *et al.*, *ibid*; Courel *et al.*, 1984; Li Sitian *et al.*,

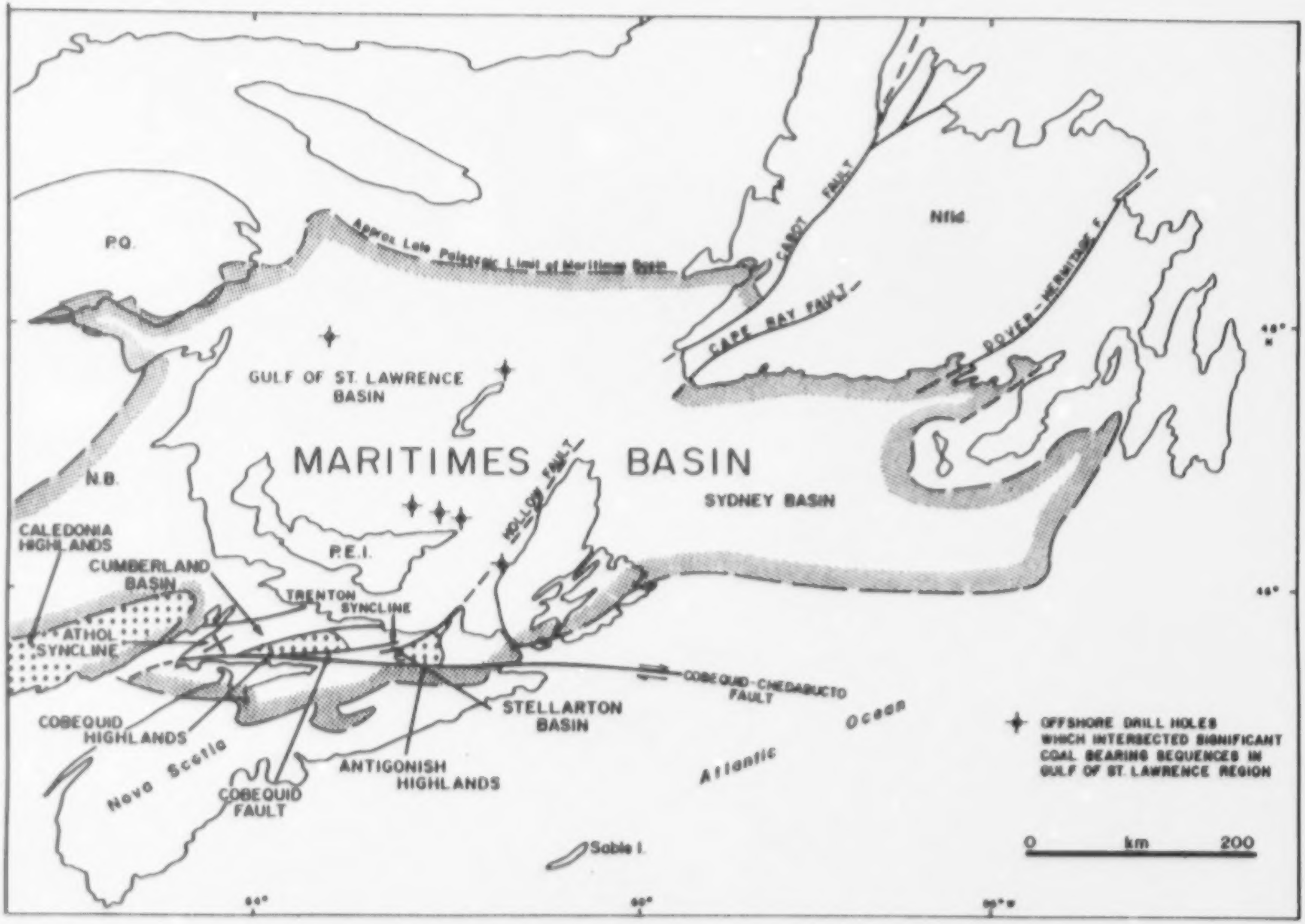

P.Q.
Approx. Late Paleozoic Limit of Maritimes Basin
Nfld.
CABOT FAULT
CAPE RAY FAULT
DOVER-HERMITAGE F.
GULF OF ST. LAWRENCE BASIN
MARITIMES BASIN
HOLLOW FAULT
SYDNEY BASIN
N.B.
CALEDONIA HIGHLANDS
P.E.I.
CUMBERLAND BASIN
TRENTON SYNCLINE
ATHOL SYNCLINE
COBEQUID-CHEDABUCTO FAULT
STELLARTON BASIN
COBEQUID HIGHLANDS
Nova Scotia
ANTIGONISH HIGHLANDS
COBEQUID FAULT
Atlantic Ocean
OFFSHORE DRILL HOLES WHICH INTERSECTED SIGNIFICANT COAL BEARING SEQUENCES IN GULF OF ST. LAWRENCE REGION
Sable I.
0 km 200
64°
60°
56°W
48°N
46°

Figure 1. Location map showing the position of the Cumberland and Stellarton Basins and other coal basins of the regional Maritimes Basin.

1984; Cabrera and Saez, *ibid*; Courel, 1988 ; Naylor *et al*., 1990; Calder, *ibid*; McCabe, 1991)); sediment supply (Wallis, 1983; Naylor, *et al*., *ibid*)); and ground water discharge from alluvial fans (Galloway and Hobday, 1983; Calder, *ibid*).

The Cumberland and Stellarton basins of Northern Nova Scotia (Fig. 1) are excellent examples of late Carboniferous intermontane fluvial and lacustrine coal-basins respectively. This paper reviews the stratigraphy, sedimentology and depositional environments of their coal measures and subsequently discusses controls on paleomire/coal development in both basins. This research is being undertaken to develop improved exploration models for low sulphur coals in Nova Scotia.

BASIN SETTINGS AND TECTONIC ORIGINS

The Cumberland and Stellarton basins are Westphalian depocenters/sub-basins of the much larger Maritimes Basin (Fig. 1). Sedimentation within the Maritimes Basin began in the mid-Devonian and continued until at least the Permian. Alleganian thrusting in the southern and mid-Appalachians during the mid-Carboniferous was accompanied by strike-slip movement in the Canadian Appalachians. At this time local depocenters such as the Cumberland and Stellarton basins developed adjacent to major fault systems in the southern part of the Maritimes Basin.

Cumberland Basin

The known onshore areal extent of the Cumberland Basin is 5000km^2, however its actual limits have not been accurately defined. To the west and south, the basin is bounded by the Caledonia and Cobequid highlands (Fig. 1), but to the north and east, the limits of the basin are obscured by a broad regional cover of younger strata and by waters of the Gulf of St. Lawrence (Fig. 1). The Cumberland Basin comprises several east- to northeast-trending synclines separated by diapiric anticlines cored with early Carboniferous marine evaporites. The anticlines are thought to have formed adjacent to and over basement horsts which suggests that the component synclines in fact may have been, at various times in their history, individual sub-basins. The tectonic origin of the Cumberland Basin is poorly understood beyond its occurrence in a transcurrent region dominated by strike-slip faulting.

Stellarton Basin

The 120km^2 Stellarton Basin lies in a broad northeast-trending trough underlain by Carboniferous strata located between the Cobequid and Antigonish highlands (Fig. 1). The basin is bounded to the north by the Cobequid Fault, to the south by the Hollow Fault (Fig. 1) and is surrounded by older Carboniferous strata.

Structural analysis of the Hollow and eastern Cobequid fault zones by Yeo and Ruixang (1987) indicates dextral movement during the late Carboniferous. The Stellarton Basin is believed to be a pull-apart basin formed in response to this movement from late Westphalian B to at least Mid-Westphalian D. (Yeo and Ruixang, 1987).

CUMBERLAND BASIN (ATHOL SYNCLINE AREA)

Thick coal-bearing sequences are only found in the southwest part of the Cumberland Basin in the area of the Athol Syncline (Fig. 1). The Athol Syncline area is approximately 2500km^2, and includes the Joggins and Springhill coalfields. Westphalian A-B coal bearing strata within the syncline are much thicker than in other areas of the Maritimes Basin (Fig. 2). Thickening of stratigraphic units coincident with the synclinal axis, indicate that the Athol Syncline area was a local depocenter during the Westphalian A-B (Calder, 1991).

General Stratigraphy

The earliest work on the stratigraphy of the Cumberland Basin was undertaken in 1843 by Sir William Logan. He made bed by bed measurements of a

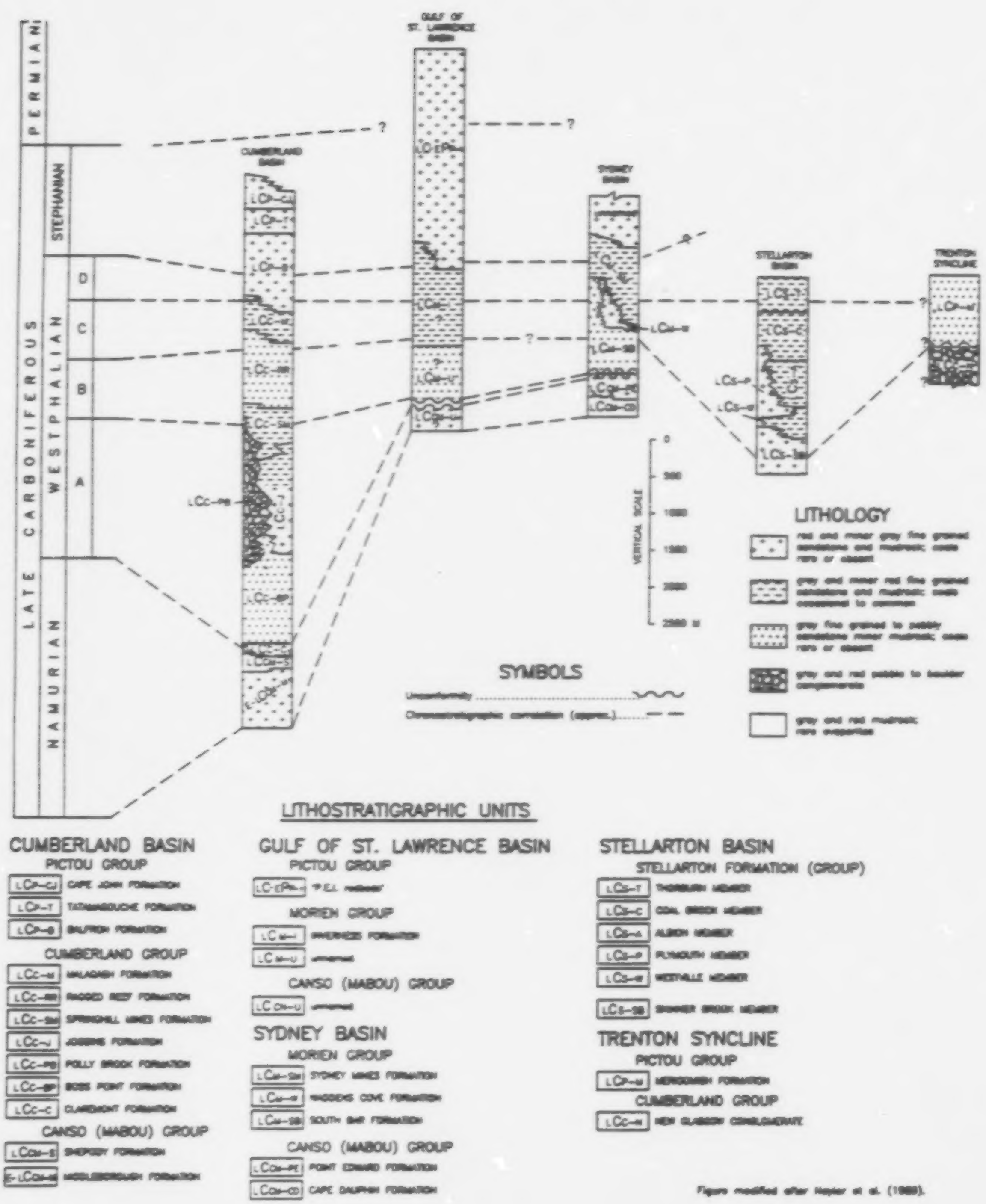

PERMIAN
LATE CARBONIFEROUS
STEPHANIAN
WESTPHALIAN
NAMURIAN
D
C
B
A
CUMBERLAND BASIN
GULF OF ST. LAWRENCE BASIN
SYDNEY BASIN
STELLARTON BASIN
TRENTON SYNCLINE
LCP-CJ
LCP-T
LCP-B
LCC-M
LCC-RR
LCC-SM
LCC-J
LCC-PB
LCC-BP
LCC-C
LCCM-S
E-LCCM-M
LC-EPR
LCM-I
LCM-U
LCCM-U
LCM-SM
LCM-W
LCM-SB
LCCM-PE
LCCM-CD
LCS-T
LCS-C
LCS-A
LCS-P
LCS-W
LCS-SB
LCP-M
LCC-N
?
VERTICAL SCALE
0
500
1000
1500
2000
2500 M
LITHOLOGY
red and minor gray fine grained sandstone and mudrock; coals rare or absent
gray and minor red fine grained sandstone and mudrock; coals occasional to common
gray fine grained to pebbly sandstone; minor mudrock; coals rare or absent
gray and red pebble to boulder conglomerate
gray and red mudrock; rare evaporites
SYMBOLS
Unconformity
Chronostratigraphic correlation (approx.)
LITHOSTRATIGRAPHIC UNITS
CUMBERLAND BASIN
PICTOU GROUP
LCP-CJ CAPE JOHN FORMATION
LCP-T TATAMAGOUCHE FORMATION
LCP-B BALFRON FORMATION
CUMBERLAND GROUP
LCC-M MALAGASH FORMATION
LCC-RR RAGGED REEF FORMATION
LCC-SM SPRINGHILL MINES FORMATION
LCC-J JOGGINS FORMATION
LCC-PB POLLY BROOK FORMATION
LCC-BP BOSS POINT FORMATION
LCC-C CLAREMONT FORMATION
CANSO (MABOU) GROUP
LCCM-S SHEPODY FORMATION
E-LCCM-M MIDDLEBOROUGH FORMATION
GULF OF ST. LAWRENCE BASIN
PICTOU GROUP
LC-EPR "P.E.I. redbeds"
MORIEN GROUP
LCM-I INVERNESS FORMATION
LCM-U unnamed
CANSO (MABOU) GROUP
LCCM-U unnamed
SYDNEY BASIN
MORIEN GROUP
LCM-SM SYDNEY MINES FORMATION
LCM-W WADDENS COVE FORMATION
LCM-SB SOUTH BAR FORMATION
CANSO (MABOU) GROUP
LCCM-PE POINT EDWARD FORMATION
LCCM-CD CAPE DAUPHIN FORMATION
STELLARTON BASIN
STELLARTON FORMATION (GROUP)
LCS-T THORBURN MEMBER
LCS-C COAL BROOK MEMBER
LCS-A ALBION MEMBER
LCS-P PLYMOUTH MEMBER
LCS-W WESTVILLE MEMBER
LCS-SB SKINNER BROOK MEMBER
TRENTON SYNCLINE
PICTOU GROUP
LCP-M MERIGOMISH FORMATION
CUMBERLAND GROUP
LCC-N NEW GLASGOW CONGLOMERATE

Figure modified after Hayes et al. (1989).

Figure 2. Lithostratigraphy and biostratigraphy of the major coal basins of Atlantic Canada.

4600m thick sequence of late Carboniferous strata that is continuously exposed along the coast of Chignecto Bay (Fig. 3). Ryan *et al.*, (1991) recently reviewed and revised the stratigraphy of the late Carboniferous to Permian strata in the Cumberland Basin. The formations proposed by Ryan *et al.* are used in this paper.

The Athol Syncline area of the Cumberland Basin contains the thickest (8000m) uninterrupted succession of Carboniferous strata known in Atlantic Canada. Coal seams occur in the upper part of the succession, but are found predominately within the Joggins and Springhill Mines formations of the Cumberland Group (Figs. 2 and 4). The Westphalian A Joggins Formation is conformably overlain by, and locally in diachronous contact with, the Westphalian A-B Springhill Mines Formation (Fig. 4). Near the southern basin margin both formations are in diachronous contact with the thick conglomerate sequences of the Polly Brook Formation (Figs. 3 and 4). The stratigraphy of the Joggins and Springhill Mines formations is typical of many intermontane successions. Rapid lateral facies changes are common and coals are best developed in narrow linear zones parallel to the long axis of the basin. The coals of the Joggins Formation are thickest and most numerous basinward whereas the Springhill Mines Formation coals are best developed adjacent to the southern basin margin.

Joggins Formation: Stratigraphy and Sedimentology

The type section of the Joggins Formation is 1433m thick and located along the northeast coast of Chignecto Bay (Ryan *et al.*, 1991). The Formation comprises grey and red mudrock interbedded with thin (<1m) grey sandstone and occasional multistorey sandstone. The lower half of the member is predominately red mudrock and grey sandstone. The upper half of the section includes a much higher percentage of grey beds and contains coals that are commonly overlain by bivalve-bearing black shales and fossiliferous limestones. The Joggins Formation can be informally subdivided into three members: the Little River, Maccan Railroad and Coal Mine Point members (Fig. 3).

Little River Member

The Little River Member has a maximum thickness of 900m and consists of 3 to 12m thick sequences of fine- to coarse-grained multistorey sandstone interbedded with 10 to 80m thick sequences of red mudrock with thin grey sandstone interbeds. The sedimentology of the Little River Member has not been studied in detail.

Maccan Railroad Member

Basinward the upper part of the Little River Member is split by the 195m thick coal-bearing Maccan Railroad Member (Fig. 3). The Maccan Railroad Member is composed of strata that combines elements of both the Little River Member and the major coal-bearing member of the Joggins Formation, the Coal Mine Point Member (Fig. 3). Three types of lithofacies assemblages comprise the Maccan Railroad Member (Fig. 5): (1) red mudrock with or without thin (<1m) interbeds of red to grey fine-grained sandstone (CF Little River Member), (2) thick (3-5m) grey fine- to coarse- grained multistorey sandstone (CF Little River Member) and (3) grey mudrock and thin sandstone interbedded with thin coals (.14cm max.), black pelecypod- bearing shale and limestone (CF Coal Mine Point Member).

The red mudrock of the Maccan Railroad Member has .02 to .50cm interbeds of carbonaceous claystone (Fig. 5) that can be underlain by rooted horizons or calcareous nodules. The thin sandstones interbedded with red mudrock occasionally contain upright fossil trees.

The thick multistorey sandstone bodies have intraformational clasts and large transported fossil trees occurring near the storey/channel bases (Fig. 5). Hollow/scour-fills mostly consisting of red mudrock are common at the top of sandstone bodies. Multistorey sandstones have a limited lateral extent and typically pinch out laterally at outcrop scale.

Coals are commonly overlain by black shale and limestone (Fig. 5) containing fresh water ostracodes, bivalves, fish fragments, spirobids, arthropods, arachnids and algal material (Dawson, 1878; Copeland, 1957; Carroll *et al.*, 1972; Duff and Walton, 1973). The limestones and black shales are often

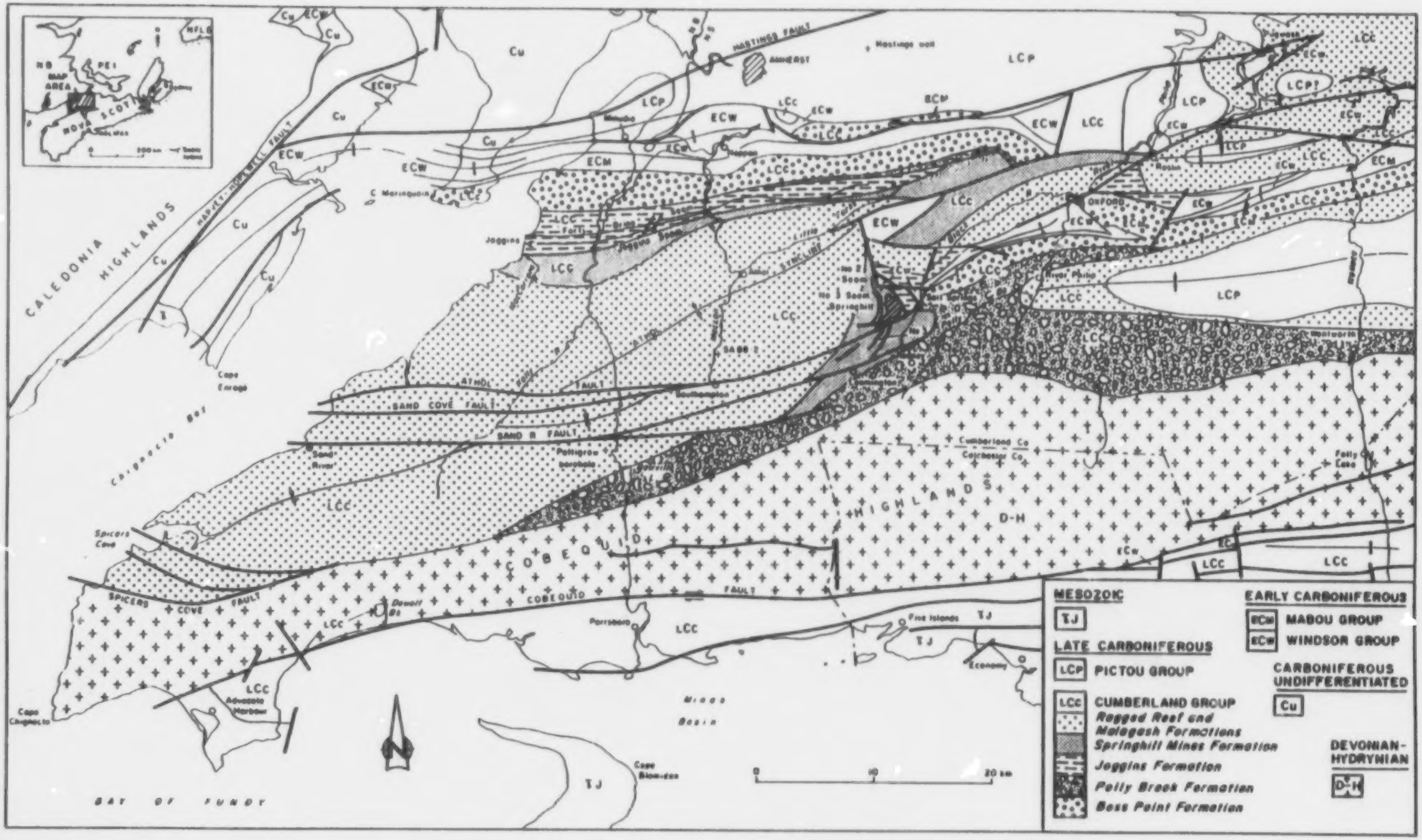

MESOZOIC
TJ
LATE CARBONIFEROUS
LCP PICTOU GROUP
LCC CUMBERLAND GROUP
Ragged Reef and Malagash Formations
Springhill Mines Formation
Joggins Formation
Polly Brook Formation
Boss Point Formation
EARLY CARBONIFEROUS
ECM MABOU GROUP
ECW WINDSOR GROUP
CARBONIFEROUS UNDIFFERENTIATED
Cu
DEVONIAN-HYDRYNIAN
D-H
0
10
20 km
CALEDONIA HIGHLANDS
HARVEY-HOPEWELL FAULT
HASTINGS FAULT
AMHERST
Joggins
Cape Enrage
Chignecto Bay
Spicers Cove
SPICERS COVE FAULT
SAND COVE FAULT
SAND R FAULT
ATHOL
COBEQUID HIGHLANDS
COBEQUID FAULT
Parrsboro
Five Islands
Economy
Minas Basin
Cape Blomidon
Cape Chignecto
Advocate Harbour
BAY OF FUNDY
OXFORD
Springhill
Cumberland Co
Colchester Co
NB
PEI
MAP AREA
NOVA SCOTIA
NFLD

Figure 3. General geology of the western Cumberland Basin.

overlain by grey mudrocks with siderite bands that coarsen upward to interbedded sandstone and mudrock (Fig. 5). The sandstone interbeds can exhibit either; trough-cross, convolute, planar or ripple bedding. Parting lineations, and groove marks occur on some sandstone bedding surfaces and upright trees are locally common (Fig. 5). The planar and ripple bedded sandstones that show gradual lateral changes in bed thickness have been described as sheet sandstones. (Duff and Walton, 1973; Gibling, 1987). The sheet sandstones are commonly eroded into by trough-cross bedded sandstones that are generally laterally restricted. Grey mudrocks with thin (<10 cm) interbeds of carbonaceous claystone are in close proximity to red beds (Fig. 5).

Coal Mine Point Member

The uppermost member of the Joggins Formation , the Coal Mine Point Member, has a maximum thickness of 490m (Fig. 4). The member is predominantly composed of grey sandstone and mudrock and contains a total of 32 coal seams 0.05 to 1.5m thick. Much of the strata that comprise the Coal Mine Point Member are similar to the grey coal-bearing sequences of the Maccan Railroad Member. The major differences are that the Coal Mine Point Member contains: 1) more coals, 2) thicker coals, 3) a much lower percentage of red-beds and 4) a higher percentage of sandstone. Limestones and black shales are still commonly found in close association with coals and sandstone beds have a tendency to be relatively thin and interbedded with grey mudrock.

Joggins Formation: Depositional Environments

The strata that comprise the lower half of the Joggins Formation are predominately fluvial deposits whereas the coal-bearing upper half of the Formation is composed of a mixture of fluvial and lacustrine deposits.

Little River Member

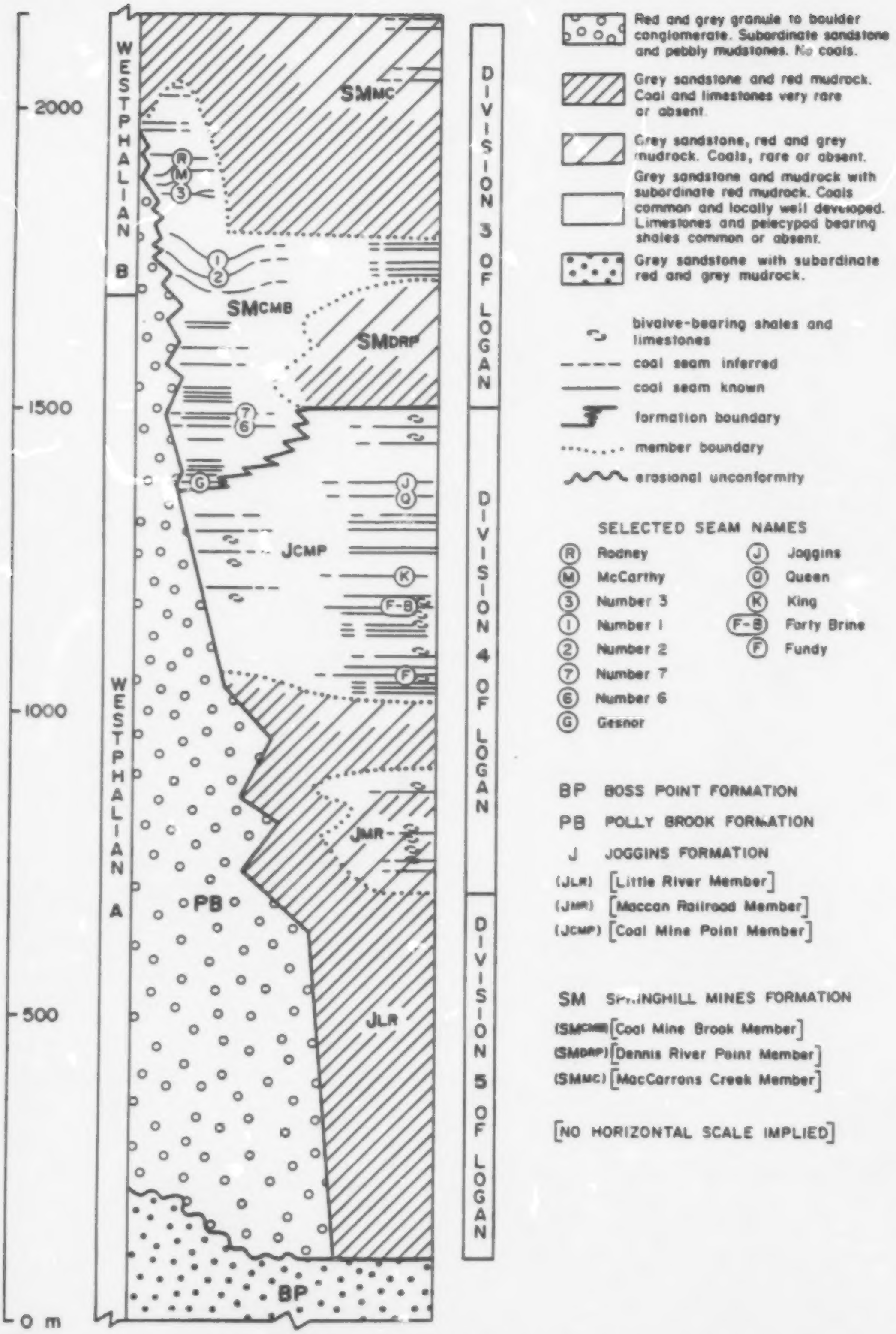
The Little River Member of the Joggins Formation is dominated by channel (thick sandstone) and floodplain deposits (mudrock interbedded with thin sandstone). Not enough detail is known about the sedimentology of the Little River Member to determine with certainty in what type(s) of channels the thick sandstones were deposited. Thick (80m max.) sequences of floodplain deposits without intervening channels may indicate that the channels of the Little River Member have low width to depth ratios. The predominance of red mudrocks within the Little River Member and the scarcity of coals and limestones suggests that the floodplains were generally well drained.

Maccan Railroad Member

The red mudrock and thin red-grey sandstone of the Maccan Railroad Member are probably well drained floodplain deposits similar to those of the Little River Member. Evidence that the floodplains were vegetated include: upright fossil trees within some thin sandstone beds, and roots and rhizoconcretions under thin interbeds of carbonaceous claystone. The thin carbonaceous claystones were likely deposited in swamps that formed when floodplains temporarily became more poorly drained.

Low width to depth ratios, stepped bases, and the multistoried nature of many of the thick channel sandstones of the Maccan Railroad Member suggest channels accreted vertically. (cf Rust *et al.*, 1984). The occurrence of mudstone filled hollows and channel lags at various levels within channels suggests episodic abandonment and reactivation.

The thick coal-bearing grey bed sequences of the Maccan Railroad Member include mire, lacustrine and floodplain deposits. The occurrence of thin coals overlain by limestones and fossiliferous black shales suggests that although short-lived mires developed on floodplains, peat accumulation rates were unable to keep pace with a relative rise in the water table. The lakes in which the limestone and black shale were deposited must have had restricted sediment supplies to allow concentrated accumulation of carbonate and organic matter. Roots within some black shale and limestone beds suggest that the lakes were either always shallow or prone to extreme depth fluctuations. No marine biota have been identified and faunal assemblages of the limestone and black shale


2000
1500
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0 m
WESTPHALIAN B
WESTPHALIAN A
DIVISION 3 OF LOGAN
DIVISION 4 OF LOGAN
DIVISION 5 OF LOGAN
SMMC
SMCMB
SMDRP
JCMP
JMR
JLR
PB
BP
R
M
3
1
2
7
6
G
J
Q
K
F-B
F
Red and grey granule to boulder conglomerate. Subordinate sandstone and pebbly mudstones. No coals.
Grey sandstone and red mudrock. Coal and limestones very rare or absent.
Grey sandstone, red and grey mudrock. Coals, rare or absent.
Grey sandstone and mudrock with subordinate red mudrock. Coals common and locally well developed. Limestones and pelecypod bearing shales common or absent.
Grey sandstone with subordinate red and grey mudrock.
bivalve-bearing shales and limestones
coal seam inferred
coal seam known
formation boundary
member boundary
erosional unconformity
SELECTED SEAM NAMES
R Rodney
M McCarthy
3 Number 3
1 Number 1
2 Number 2
7 Number 7
6 Number 6
G Gesnor
J Joggins
Q Queen
K King
F-B Forty Brine
F Fundy
BP BOSS POINT FORMATION
PB POLLY BROOK FORMATION
J JOGGINS FORMATION
(JLR) [Little River Member]
(JMR) [Maccan Railroad Member]
(JCMP) [Coal Mine Point Member]
SM SPRINGHILL MINES FORMATION
(SMCMB) [Coal Mine Brook Member]
(SMDRP) [Dennis River Point Member]
(SMMC) [MacCarrons Creek Member]
[NO HORIZONTAL SCALE IMPLIED]

Figure 4. General stratigraphy of the Polly Brook, Joggins and Springhill Mines Formation in the Athol Syncline area of the western Cumberland Basin.

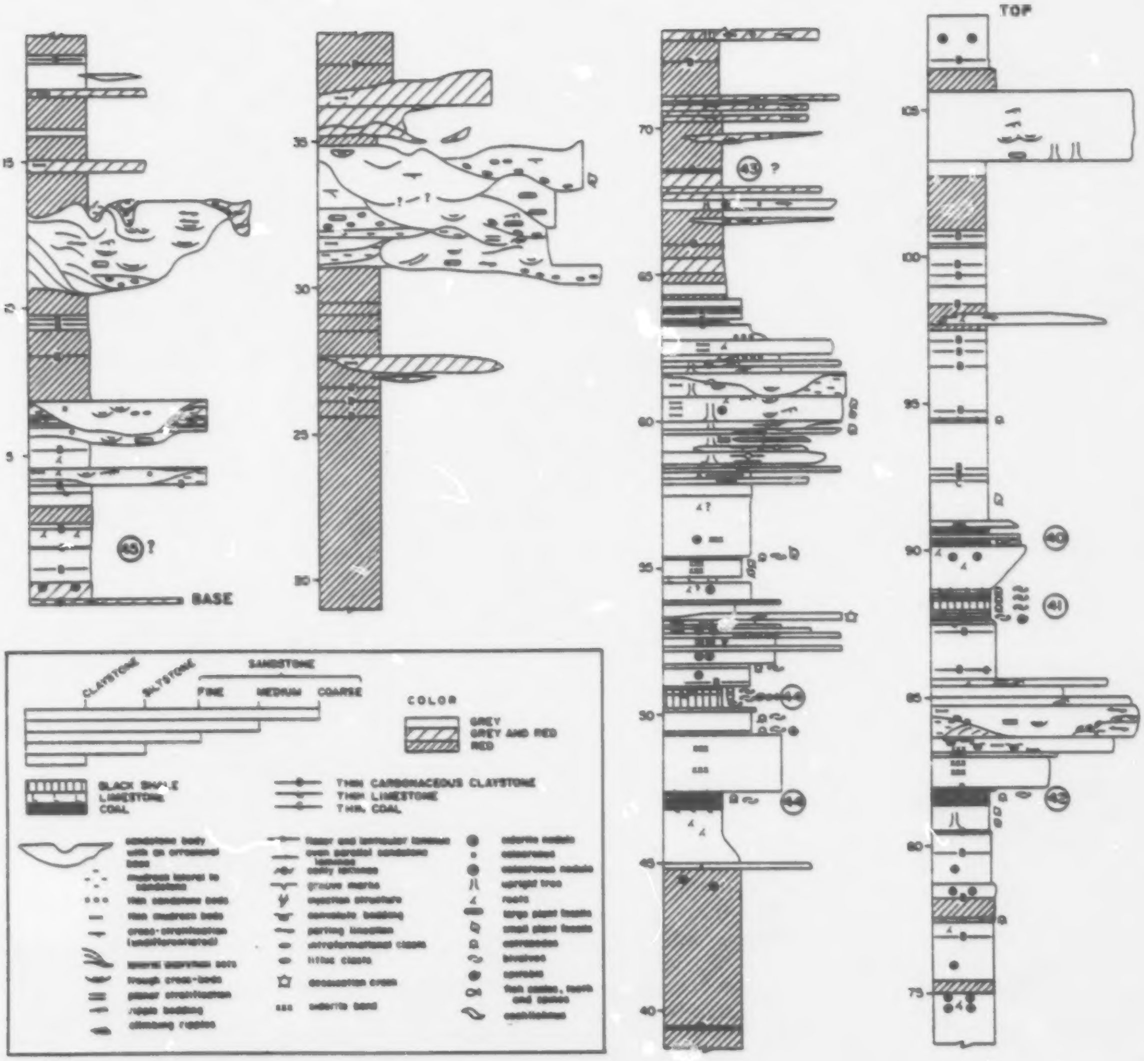
TOP
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
BASE
45 ?
43 ?
44
44
40
41
42
CLAYSTONE
SILTSTONE
SANDSTONE
FINE
MEDIUM
COARSE
COLOR
GREY
GREY AND RED
RED
BLACK SHALE
LIMESTONE
COAL
THIN CARBONACEOUS CLAYSTONE
THIN LIMESTONE
THIN COAL

Figure 5. Vertical profile illustrating the sedimentology of the lower 107m of the Maccan Railroad Member (Joggins Formation) northeast coast of Chignecto Bay. Circled numbers beside profile correspond to Logan (1845).

indicate fresh water to brackish conditions (Duff and Walton, 1973). Low faunal diversity indicates the lake environment was relatively harsh (Gibling, 1987).

Lacustrine deposits within the Maccan Railroad Member are probably not restricted to limestones and black shales. Some of the coarsening upward mudrock to sandstone sequences may in fact be lacustrine delta deposits. An example of a probable lacustrine delta sequence overlies coal number 42 to about 85m (Fig.5). Evidence supporting a lacustrine delta origin includes the absence of roots and upright fossil trees. The mudrock with siderite bands at the base of the sequence mark the initial diversion of clastic-bearing channels into a previously sediment-starved lake. As the lacustrine delta prograded into the lake a coarsening upward sequence was formed and capped by a thin distributary channel sandstone. Tye and Coleman (1989) have described similar deltaic sequences that are formed by mouth bar deltas that are currently infilling shallow lakes in the Atchafalaya Basin.

The grey mudrocks and thin sandstones of the Maccan Railroad Member are not all lacustrine fill deposits. Numerous upright fossil trees and roots within some interbedded sandstone and mudrock sequences (Fig. 5) suggest that the common occurrence of crevasse splay and levee deposits. Thin laterally discontinuous sandstones that erode into crevasse/levee sequences are small distributary and/ or crevasse channels.

Coal Mine Point Member

The grey beds of the Maccan Railroad Member and the strata comprising the Coal Mine Point Member, appear to consist of similar types of deposits. The overall increase in thickness and abundance of both sandstones and coals within the Coal Mine Point Member indicates: more frequent and lengthy periods of mire development alternated with relatively rapid deposition of floodplain clastics. Limestone and black shale roofs over some coals again suggest mire growth was terminated by a water table rise and formation of perennial sediment starved lakes. Many coals of the Coal Mine Point Member however are overlain directly by lacustrine delta or crevasse splay/levee sequences suggesting rapid sediment accumulation over mires. Rare thick multistorey sandstones are the first significant channel sandstones of the Joggins Formation not closely associated with red beds.

Joggins Formation: Paleogeography

The depositional environments of the lower Joggins Formation (Little River Member) are largely unknown. General stratigraphic relationships however give some idea of the paleogeography of the Athol Syncline area during this period. While the Little River Member was being deposited, alluvial fans of the Polly Brook Formation were shed off the Cobequid highlands well out into the basin. This suggests that significant highlands existed adjacent the basin during deposition of the Little River Member. Progressive onlap of the Little River Member toward the southern basin margin (Fig. 3) supports an interpretation of gradual denudation and eroding back of highland areas. As alluvial fans receded floodplain areas became larger and lakes, swamps and mires began to develop.

Figure 6 illustrates the general paleogeography of the western Cumberland Basin during deposition of the Coal Mine Point Member of the Joggins Formation. The alluvial fans of the Polly Brook Member still persist near Springhill. The rare occurrence of thick channel sandstones within the Coal Mine Point along Chignecto Bay suggests that if a major river zone did exist it rarely migrated as far north as Joggins. Figure 6 assumes a major trunk fluvial system did not exist during deposition of the Coal Mine Point Member. Instead, the basin floor was covered by a series of smaller river channels with well developed levees that were bordered by vegetated floodplains with shallow lakes (Fig. 6). Mires developed in areas with restricted sediment supply.

Springhill Mines Formation: Stratigraphy and Sedimentology

The Springhill Mines Formation is 600 to 800m thick (Fig. 4) and comprises two types of lithologic assemblages. Basinward along Chignecto Bay (Fig. 3) the Formation is composed of red and subordinate grey mudrocks, thin (<1m) red and grey sandstone, grey multistorey sandstone and rare thin coals. In the

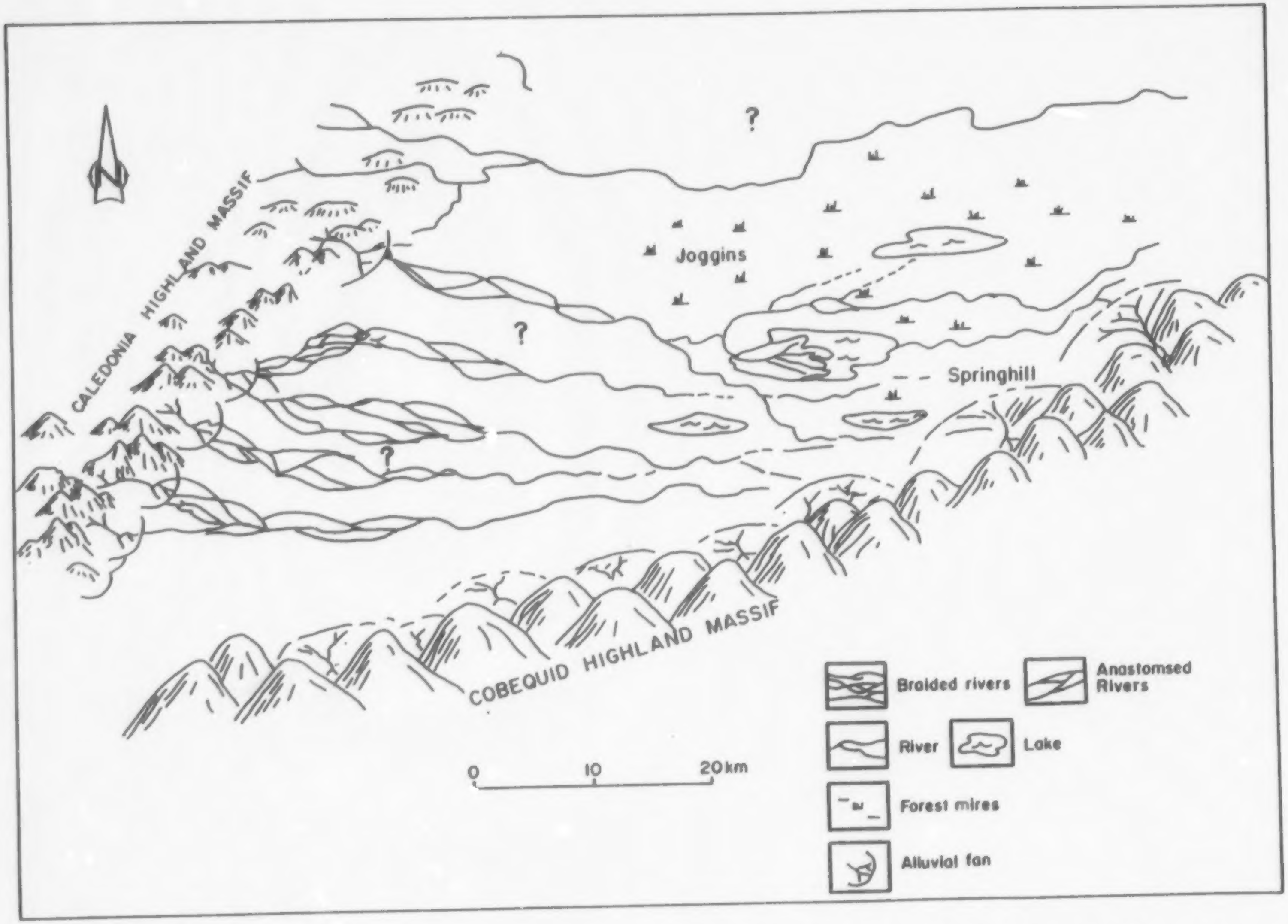
N
CALEDONIA HIGHLAND MASSIF
COBEQUID HIGHLAND MASSIF
Joggins
Springhill
?
?
?
0
10
20km
Braided rivers
Anastomsed Rivers
River
Lake
Forest mires
Alluvial fan

Figure 6. Paleogeographic model of the western Cumberland Basin during deposition of the Coal Mine Point Member of the Joggins Formation.

southeast, in the area of the Springhill coalfield (Fig. 3), the Formation comprises grey mudrock interbedded with thin (<1m) grey sandstone, grey multistorey sandstone and numerous coals. The Springhill Mines Formation can be informally subdivided into three members: 1) the Coal Mine Brook, 2) Dennis River Point and 3) MacCarrons River members (Fig. 4).

Coal Mine Brook Member

The Coal Mine Brook Member occurs near the southern basin margin in a 4 to 6km wide zone that parallels the margin of the basin with the Cobequid highlands. At Springhill the member reaches a thickness of 660m. Basinward along Chignecto Bay the Coal Mine Brook Formation thins and is in diachronous contact with the largely non-coal-bearing MacCarrons River and Dennis River Point members. (Fig. 4). The stratigraphy and sedimentology of the Coal Mine Brook Member has been described in detail by Calder, (1991) therefore only a brief review is presented here.

Grey sandstones, grey mudrocks and humic coals comprise almost all of the Coal Mine Brook Member, occurring as repetitive, non-marine cyclothems 11 to 38m thick (Fig. 7). At least 60 coal seams, ranging from 0.05 to 4.32m, occur within the Coal Mine Brook Member. The thickest coals are found in the Springhill coalfield in close association with thick (3 to 22m) multistorey sandstone bodies that are laterally persistent for distances of 1 to 4km. Basinward coals split around sequences of mudrock and multistorey sandstone up to 22m in thickness. Toward the southern basin margins seams interfinger with poorly sorted pebbly sandstone and mudrock. Rare non-fossiliferous limestones exhibiting cone-in-cone structure occur as thin discontinuous lenticular bodies, commonly within sideritic mudrocks overlying coals. Red beds (mudrock) are rare.

Dennis River Point Member

The Dennis River Point Member (Fig. 4) of the Springhill Mines Formation has a maximum thickness of 215m and is comprised of grey sandstone, red and grey mudrock and very rare thin coals. The sedimentology of the Dennis River Point Member has not been studied in detail. The unit is important however as it marks the disappearance of the relatively thick coals and limestones that are so common in the underlying Coal Mine Point Member.

MacCarrons River Member

The MacCarrons River Member (Fig. 4) has a maximum thickness of 370m and comprises red with subordinate grey mudrocks and grey sandstones. Rust et *al*., 1984 recognized two types of facies associations within the MacCarrons River Member: (1) thick (3-11m) multistorey and laterally restricted sandstone bodies with stepped erosional bases, (2) thin (<1.5m) sheet sandstones interbedded with red and grey mudrock, carbonaceous claystone and coals (Fig. 8). The thick sandstones are fine- to coarse-grained, predominately trough-cross stratified and generally exhibit no vertical trends with respect to grain size, bed thickness, or scale of sedimentary structures (Rust et *al*., 1984) (Fig. 8). Lateral accretion sets are very rare and only occur near the top of a few of the sandstone bodies. (Rust et *al*., 1984).

The sheet sandstones are predominately fine grained ripple bedded and contain roots. They can either fine upward, coarsen upward or fine and then coarsen upward. Mudrocks interbedded with the sheet sandstones are most commonly red, rarely exceed 2m in thickness and generally contain roots. Silty mudrocks can contain thin ripple laminae. The few coals that occur within the MacCarrons River Member are less than 10cm in thickness.

Springhill Mines Formation: Depositional Environments

Fluvial deposits comprise most of the Springhill Mines Formation. Significant differences exist however in the types of fluvial deposits that make up the various members.

Coal Mine Brook Member

Calder, (1991) provides a detailed discussion of the depositional

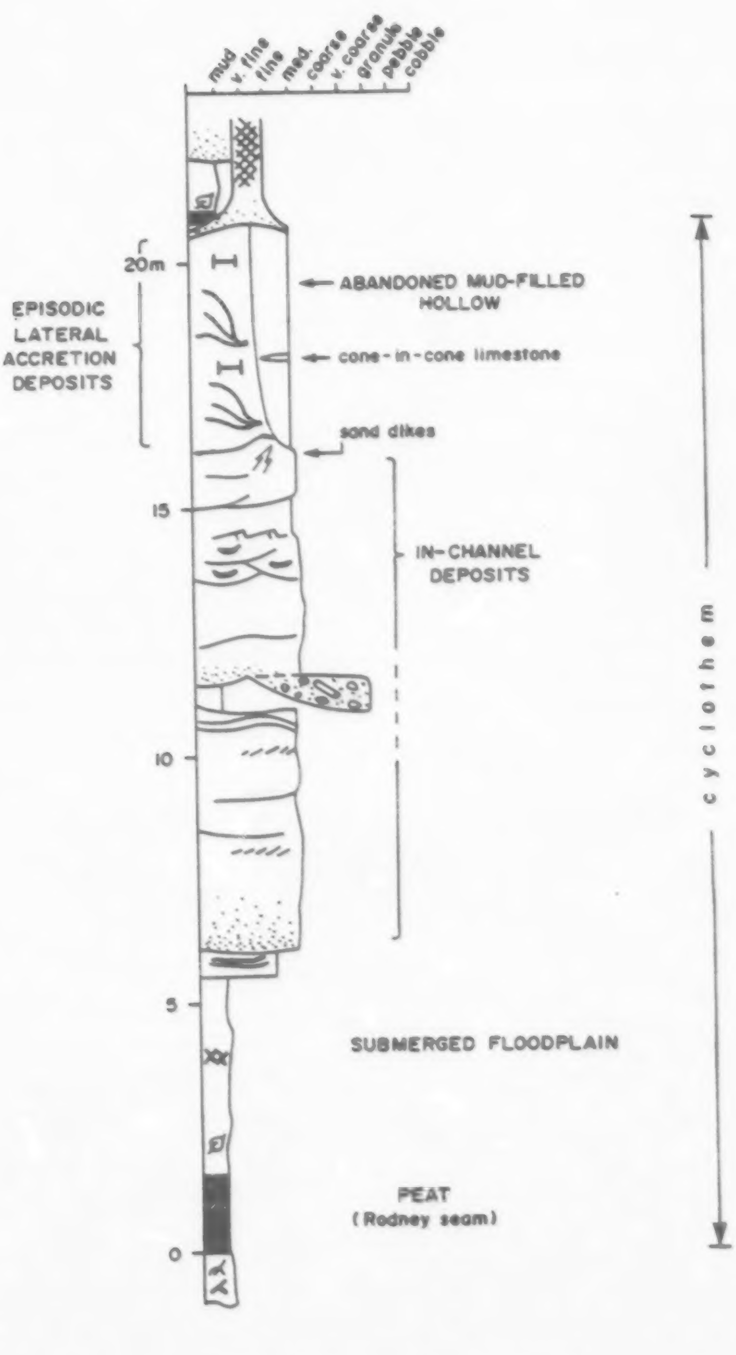
mud
v. fine
fine
med.
coarse
v. coarse
granule
pebble
cobble
20m
15
10
5
0
EPISODIC LATERAL ACCRETION DEPOSITS
ABANDONED MUD-FILLED HOLLOW
cone-in-cone limestone
sand dikes
IN-CHANNEL DEPOSITS
SUBMERGED FLOODPLAIN
PEAT
(Rodney seam)
cyclothem

Figure 7. Vertical profile illustrating the sedimentology of a typical "cyclothem" from the Coal Mine Brook Member of the Springhill Mines Formation (after Calder, 1991) see Fig. 5 for explanation of symbols.

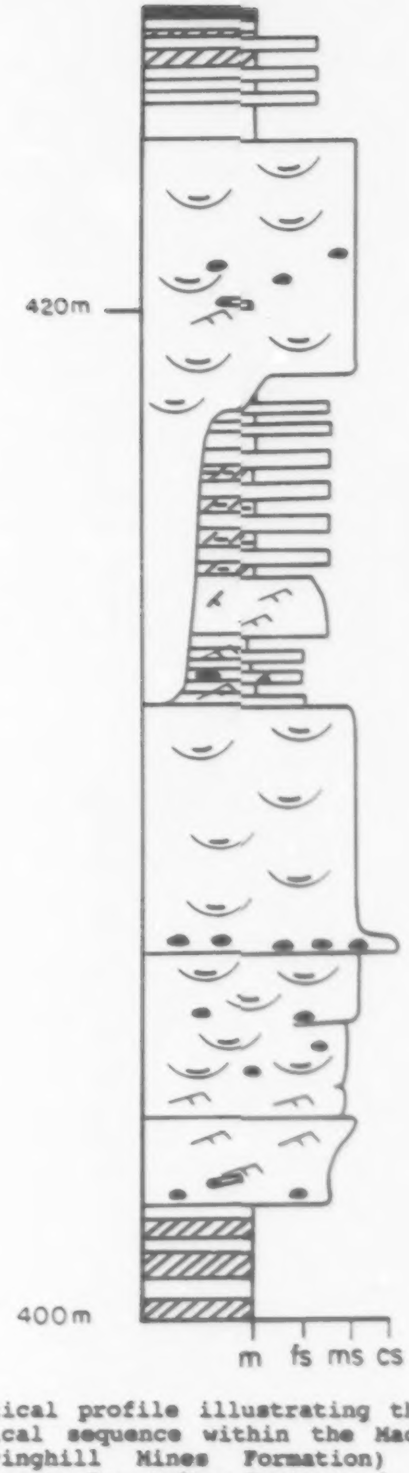

Figure 8. Vertical profile illustrating the sedimentology of a typical sequence within the MacCarrons River Member (Springhill Mines Formation) northeast coast of Chignecto Bay (after Rust et *al.*, 1984) see Fig. 5 for explanation of symbols.

environments of the Coal Mine Brook Member of the Springhill Mines Formation thus only a brief review is presented here. The organic petrology and palynology of the coals suggest they formed from rheotrophic mires (Calder, 1991). The siderite-bearing organic-rich mudrock that usually directly overlie the coals (Fig. 7) are believed to be deposits of perennially saturated or submerged floodplains. Similar muds have been described by (Coleman, 1966) from poorly drained, perennially flooded wetlands of the Atchafalay river basin. Thin interbeds of horizontal and ripple-bedded sandstone within sideritic mudrock sequence, were interpreted by Calder to be proximal floodplain deposits (i.e. crevasse splays and levees).

The multistorey sandstones of the Coal Mine Brook Member are deposits of river channels that were prone to flash floods. Episodic lateral accretion deposits and abandoned mudrock filled hollows at the top of some sandstone bodies (Fig. 7) suggest a periodic high degree of river sinuosity. The thin cone-in-cone limestones contained within some hollow fills (Fig. 7) are believed to have formed in channel cut-offs that lacked sediment input. Many of the coal seams of the Coal Mines Brook Member split basinward around channel sandstone and floodplain deposits.

Dennis River Point Member

Further work is required to determine the depositional environments of the deposits that comprise the Dennis River Point Member. Generally however it is believed to be composed of deposits broadly similar in origin to those described below for the MacCarrons River Member.

MacCarrons River Member

Rust *et al.*, (1984) suggested that the thick multistorey sandstones of the MacCarrons River Member are primarily deposits of vertically accreting channels of anastomosed rivers. The evidence for vertical accretion is identical to that previously listed for the thick channel sandstones of the Maccan Railroad Member. The sheet sandstones of the MacCarrons River Member are levee and crevasse splay deposits. Levees are characterized by upright trees and coarsening-upward sequences, crevasse splays by fining or coarsening then fining upward sequences. (Rust *et al.*, 1984). Mudrock with roots and mudrock with thin ripple laminae are interpreted to be floodbasin deposits.

Frequent introduction of crevasse splays into floodplain appear to have limited the maximum thickness of mudrock units to approximately 2m. Rust *et al.*, (1984) suggests that this is consistent with floodplains of anastomosed rivers which are never far from a major channel. Abundant roots within mudrocks indicates distal areas of the floodplains (i.e. floodbasins) were frequently vegetated. The high percentage of red mudrocks suggests floodplains were generally well drained causing oxidation of organic matter. The rare occurrence of thin coals and carbonaceous mudrocks suggest more poorly drained and reducing conditions were not common.

Springhill Mines Formation: Paleogeography

Figure 9 illustrates the paleogeography of the western Cumberland Basin area during the period when both the MacCarrons River and Coal Mine Brook members of the Springhill Mines Formation were deposited. Alluvial fans had receded south as the Cobequid Highlands continued to erode back. Anastomosed rivers near Joggins give way to a somewhat more meandering style toward Springhill. Mires are developed in a narrow belt between the alluvial fans being shed off the Cobequids and the longitudinal river systems.

STELLARTON BASIN

The coal measures of the Stellarton Basin bear little resemblance to those of the Athol Syncline area of the Cumberland Basin. Overall the Stellarton Basin (Fig. 10) contains thicker coals, and a much higher percentage of grey fine grained strata.

Evidence that the Stellarton Basin is a localized depocenter and not a

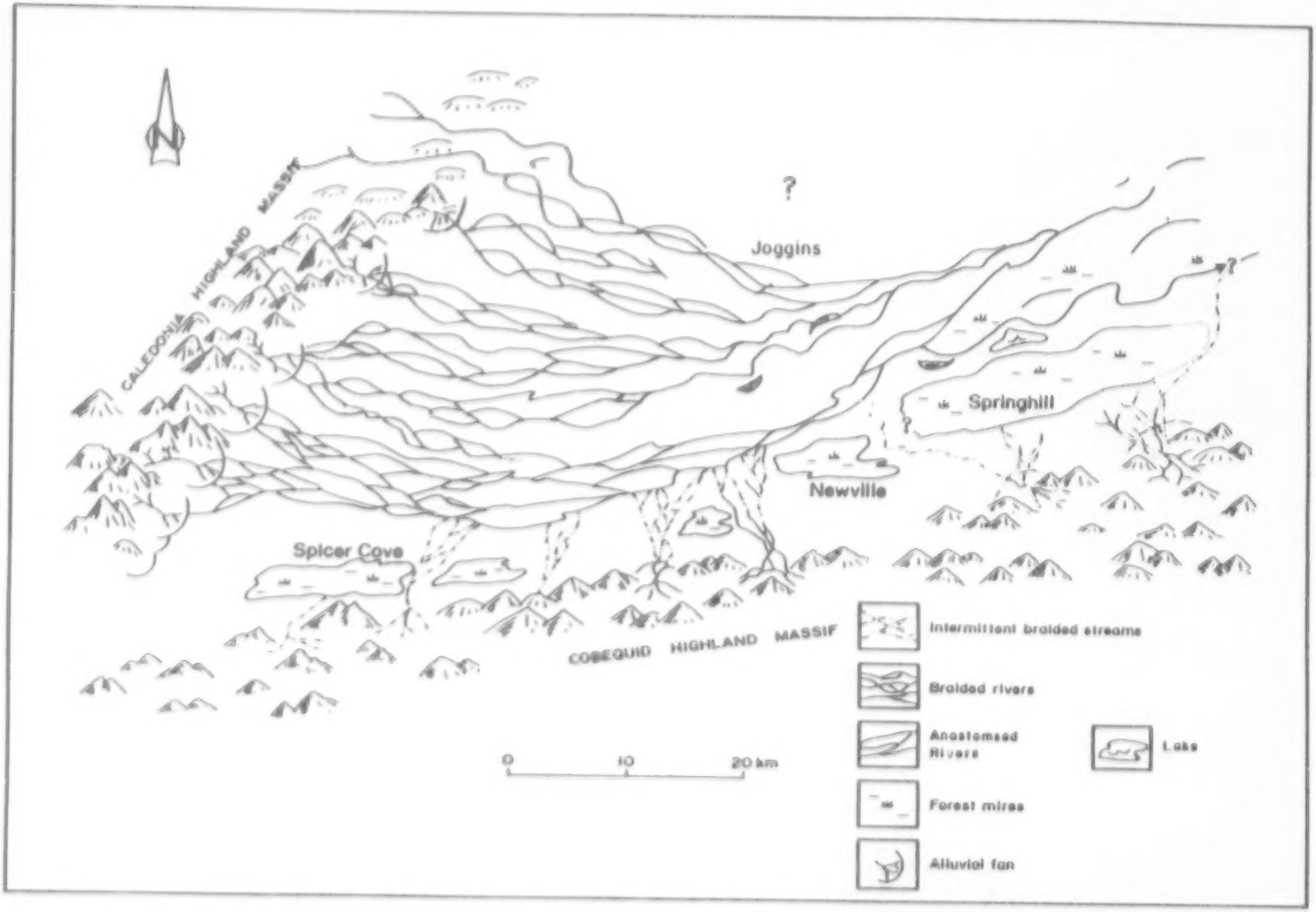
N
?
Joggins
?
CALEDONIA HIGHLAND MASSIF
Springhill
Newville
Spicer Cove
COBEQUID HIGHLAND MASSIF
0
10
20 km
Intermittent braided streams
Braided rivers
Anastomsed Rivers
Lake
Forest mires
Alluvial fan

Figure 9. Paleogeographic model of the western Cumberland Basin during deposition of the Springhill Mines Formation.

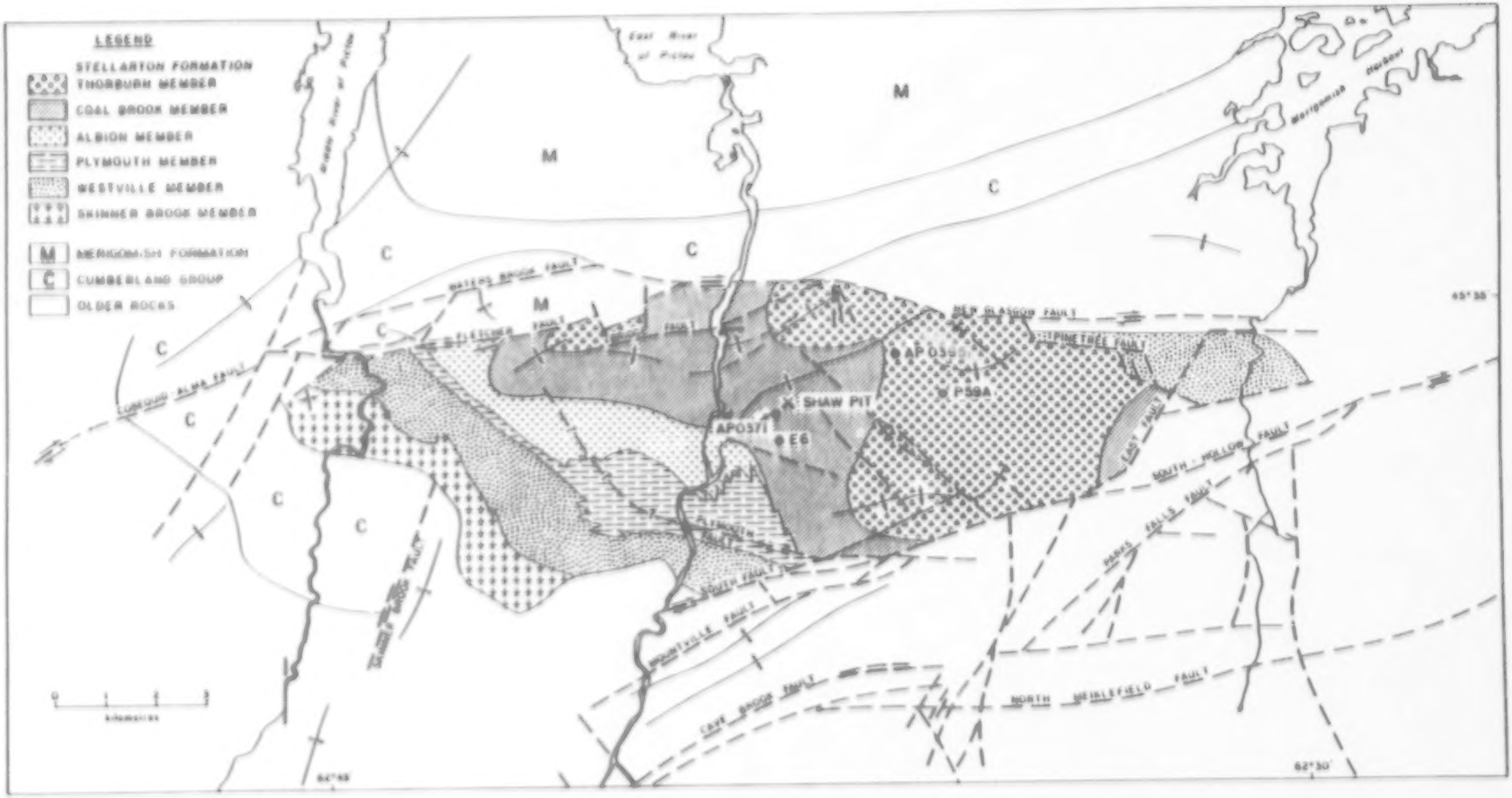
LEGEND
STELLARTON FORMATION
THORBURN MEMBER
COAL BROOK MEMBER
ALBION MEMBER
PLYMOUTH MEMBER
WESTVILLE MEMBER
SKINNER BROOK MEMBER
M MERIGOMISH FORMATION
C CUMBERLAND GROUP
OLDER ROCKS
0 1 2 3
East River of Pictou
Middle River of Pictou
Merigomish Harbour
M
C
WATERS BROOK FAULT
FLETCHER FAULT
COBEQUID ALMA FAULT
NEW GLASGOW FAULT
PINETREE FAULT
EAST FAULT
SOUTH HOLLOW FAULT
PARKS FALLS FAULT
SOUTH FAULT
WESTVILLE FAULT
CAVE BROOK FAULT
NORTH WEIBLEFIELD FAULT
SKINNER BROOK FAULT
SHAW PIT
AP0371
E6
AP0355
P59A
45°35'
62°45'
62°30'

Figure 10. General geology of the Stellarton Basin showing member boundaries of the Stellarton Formation and location of key drillholes on cross sections illustrated by Figs. 12 and 13.

fault-bounded remnant of a much larger basin include: (1) rapid coarsening of strata and deterioration of many coal seams near basin margins; (2) a significantly greater thickness of basin-fill relative to coeval strata elsewhere in the Maritimes Basin (Fig. 2); (3) a pronounced lithologic difference of the basin-fill with coeval strata in the Trenton Syncline area (D'Orsay *et al.*, 1986) 2 kms north of the Stellarton Basin (Fig. 1 and 2).

General Stratigraphy

The general stratigraphy of the Stellarton Basin was described by Dawson (1878), Logan and Hartley (1869) and Poole (1904). The most comprehensive studies of the basin stratigraphy and sedimentology have been undertaken by Bell (1940) and Naylor *et al.*, (1989)

The Stellarton Basin contains 2600m of interbedded red and grey siliclclastics with numerous coals and oil shales (Fig. 11). The basin-fill sequence, is late Westphalian B through early D in age (Yeo, *et al.*, 1988) and was called the Stellarton Series by Bell (1940); however, Stellarton Formation is now used (e.g. Yeo and Ruixiang, 1987, Naylor *et al.*, 1989; Kalkreuth *et al.*, in press).

Stellarton Formation: Stratigraphy and Sedimentology

The Stellarton Formation comprises predominately grey mudrock and sandstone interbedded with oil shale and coals. (Fig. 11). Thick red bed sequences that are locally developed along basin margins interfinger abruptly toward the basin center with grey coal and oil shale-bearing sequences (Fig. 10 and 11). Thick coals are contained in the lower half of the Formation whereas thin coals and a greater abundance of oil shale occur higher in the section (Fig. 11).

Bell (1940) subdivided the Stellarton Formation into six informal members: two red bed members (Skinner Brook and Plymouth) and four coal-bearing members (Westville, Albion, Coal Brook and Thorburn). (Figs. 10 and 11). Naylor *et al.*, (1989) retained Bell's subdivision and improved the stratigraphic framework by recognizing 60 laterally continuous oil shale beds (Fig. 11).

Albion, Plymouth, Westville and Skinner Brook Members

The Albion and Westville members have a combined average thickness of approximately 1200m (Fig. 11). Both members are in diachronous contact with basin margin red bed members (Fig. 11), which contain well developed paleosols. The Albion Member consists of coal, oil shale, organic-rich and organic-poor mudrock, and grey, fine- to medium-grained sandstone. Bioturbation by roots is extensive within the Albion Member and sedimentary structures are very poorly preserved. In central areas of the basin, coal is typically overlain by oil shale or organic-rich mudrock with rare coal laminae. The organic-rich mudrock typically grades upward through grey mudrock and siltstone to fine-grained sandstone. These coarsening upward sequences can in turn fine upward to the next coal seam. Near basin margins, the red mudrock and sandstone of the Plymouth Member replace the Albion Member strata. The thickest coal seams (max. 13.4m) known within the Maritimes Basin occur in the Albion Member. The Albion Member coals are best developed toward the center of the Stellarton Basin and deteriorate rapidly toward its margins (Hacquebard and Donaldson, 1969). Organic-rich mudrocks within the Plymouth Member are very likely stratigraphic equivalents to the Albion coals. (Daigle, 1988). The lower half of the Westville Member is very similar to the Albion Member. Above the Acadia seam (Fig. 11), however, the sequence predominantly comprises rhythmically-layered mudrock and flaser- to lenticular-laminated siltstone that grade to coarsening-upward mudrock to sandstone sequences near basin margins.

Coal Brook and Thorburn Members

The Coal Brook and Thorburn members of the Stellarton Formation have a combined average thickness of approximately 1000m (Fig. 11). The lithologies constituting these two members are very similar. In central basin areas 5 to 20m thick sequences of rhythmically-layered mudrock with varve-like laminae separate oil shale beds 1 to 35m thick (Fig. 12). Closer to basin margins, the oil shale beds thin and the mudrocks are gradually replaced by grey coarsening-upward

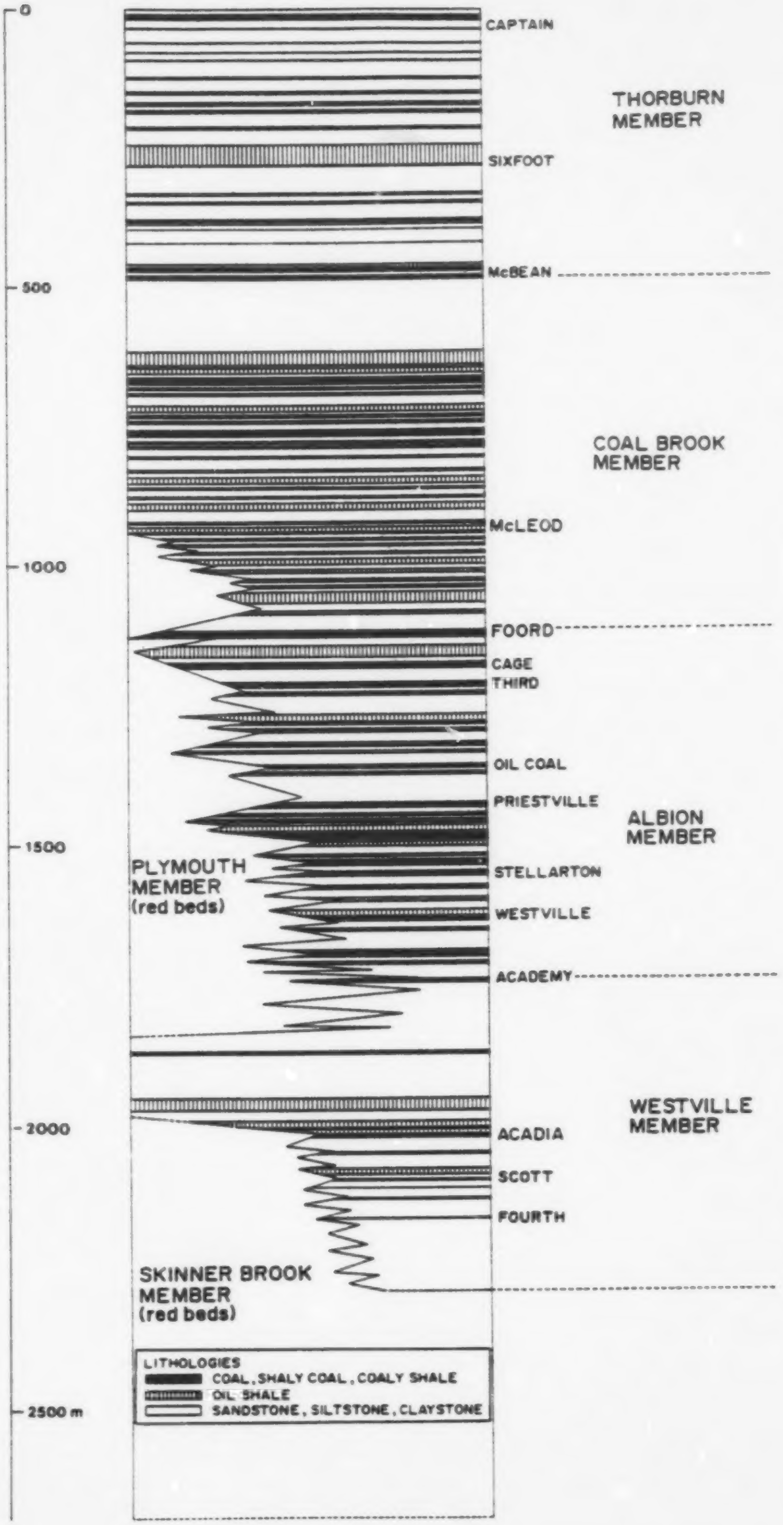
0
500
1000
1500
2000
2500 m
CAPTAIN
THORBURN MEMBER
SIXFOOT
McBEAN
COAL BROOK MEMBER
McLEOD
FOORD
CAGE
THIRD
OIL COAL
PRIESTVILLE
ALBION MEMBER
PLYMOUTH MEMBER (red beds)
STELLARTON
WESTVILLE
ACADEMY
WESTVILLE MEMBER
ACADIA
SCOTT
FOURTH
SKINNER BROOK MEMBER (red beds)
LITHOLOGIES
COAL, SHALY COAL, COALY SHALE
OIL SHALE
SANDSTONE, SILTSTONE, CLAYSTONE

Figure 11. Stratigraphy of the Stellarton Formation illustrating member boundaries and the position of coal seams and oil shale beds. Seam names are listed beside some coals.

mudrock to sandstone sequences 10 to 40m thick (Fig. 12). These coarsening-upward sequences generally consist of rhythmically-layered mudrock at the base, which grades through flaser- to lenticular-laminated siltstone and rippled fine grained sandstone to horizontally stratified fine- to medium-grained sandstone (Fig. 12). Preservation of sedimentary structures is excellent with bioturbation limited to rare pelecypod escape burrows and rooted horizons. Still closer to basin margins, mudrock with roots and cross-stratified sandstone becomes increasingly common. Immediately adjacent to basin margins, thick pebble to cobble conglomerate sequences are interbedded with cross-stratified sandstone, mudrock with roots, and coal seams. Thin pebble- to cobble-conglomerate interbedded with coarsening upward mudrock to sandstone sequences and thin oil shale beds also occur adjacent to basin margins.

The coal seams of the Coal Brook and Thorburn members are generally less than 3m thick and are few in number (Fig. 11). These coal seams are best developed toward the basin margin and are transitional to cannel shale and oil shale toward the basin centre (Naylor *et al.*, 1986; Paul *et al.*, 1989) (Fig. 13).

Stellarton Formation: Depositional Environments

Lacustrine deposits and paleomires comprise almost all of the Stellarton Formation. There is distinct change upsection from ephemeral to perennial lacustrine conditions. This in turn impacts on where mires developed within the basin.

Westville, Skinner Brook, Albion and Plymouth Members

The Westville and Albion coals formed from mires that were best developed near the basin center (Hacquebard and Donaldson, 1969). These mires were apparently rheotropic, as the high ash content and microbanded nature of the coals suggests frequent flooding. Both oil shale and organic-rich mudrock overlie Westville and Albion coals suggesting that mire development was terminated by at least two types of processes. The occurrence of oil shale directly over coals indicates that a stable sediment depleted lake drowned the mire. The organic-rich mudrock that overlie Albion and Westville coals are commonly rooted. This suggests that although the mires were not permanently drowned, sediment supply from short term floods so out paced accumulation of organic matter that peats ceased to form. Therefore, non-peat forming swamps in which organic-rich mud accumulated replaced peat-forming mires. The extensive bioturbation by roots of the coarsening-upward grey mudrock and sandstone sequences of the Westville and Albion Members indicates they were periodically vegetated. These sequences are likely composed of lacustrine delta deposits of shallow lakes. As the lakes became infilled or the water table dropped, the deltaic deposits were colonized by plants.

While the Westville and Albion mires formed toward the basin center the paleosols of the Plymouth and Skinner Brook members formed near basin margins. The predominance of red beds within these members suggests basin margins were slightly elevated and better drained relative to the central basin area. Local development of duricrusts indicates a periodically unstable water table. The lateral equivalence of some central basin coals to organic-rich mudrocks within the Skinner Brook and Plymouth members reflects a transition from mire to vegetated poorly drained swamp.

Coal Brook and Thorburn Members

The coals of the Coal Brook and Thorburn members formed from mires that only developed away from the basin center. These coals have microbanding and high ash contents similar to the Westville and Albion coals indicating they also developed from rheotropic paleomires. Thick oil shales that overlie most of the coals of the Coal Brook and Thorburn members were deposited in lakes with a restricted sediment supplies. Lateral transitions of coal to oil shale toward the basin center (Fig. 13), suggest mires formed around lake margins while organic-rich mud/oil shale was deposited in central basin lakes. Thickening of coals toward basin margins suggests gradual expansion of a central basin lake slowly drowned the mires.

The clastic sequences that separate the oil shale beds are largely

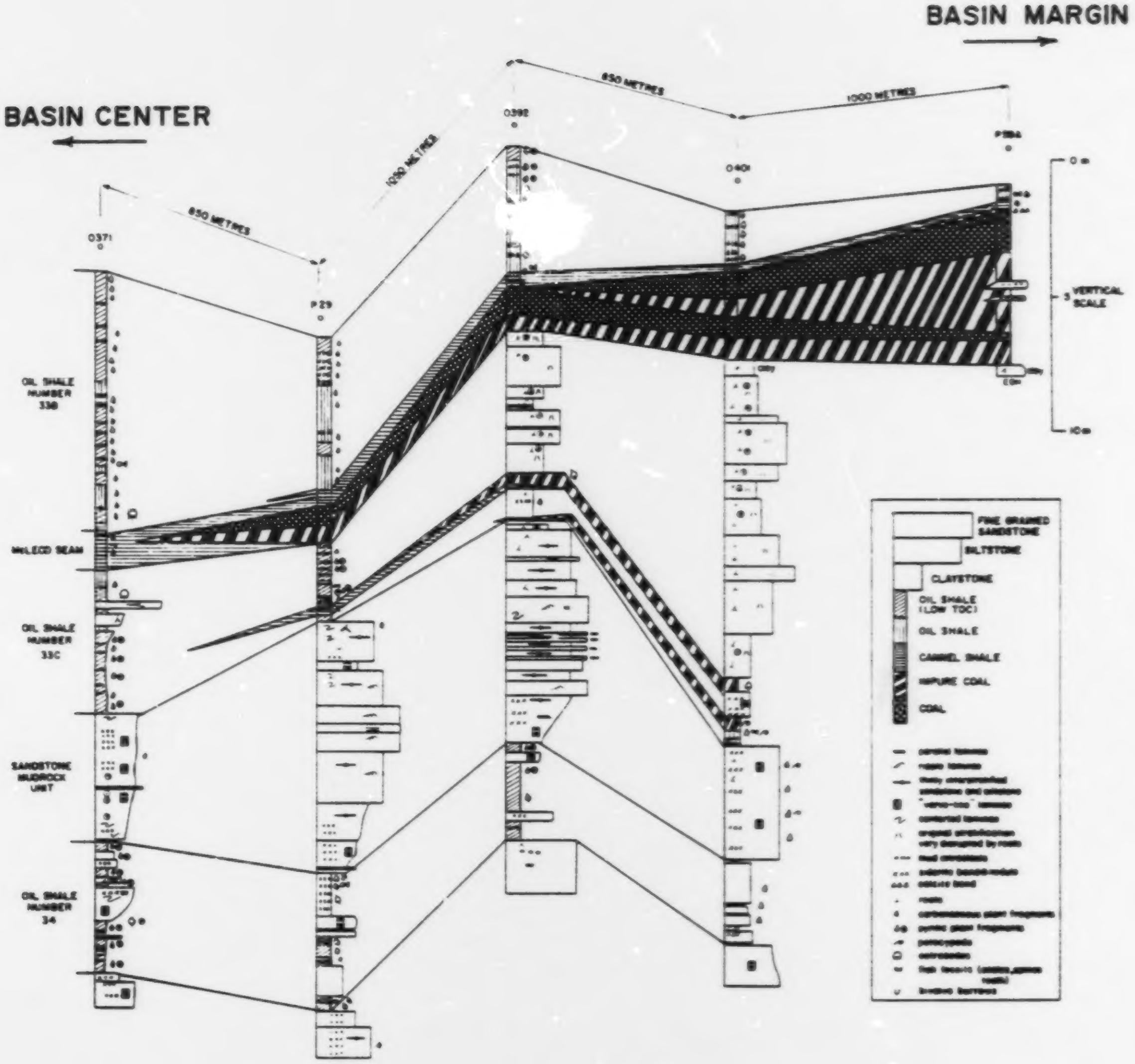
BASIN MARGIN
BASIN CENTER
850 METRES
1000 METRES
850 METRES
1000 METRES
0371
P29
0392
0401
P59A
0 m
5
VERTICAL SCALE
10 m
OIL SHALE NUMBER 33B
McLEOD SEAM
OIL SHALE NUMBER 33C
SANDSTONE MUDROCK UNIT
OIL SHALE NUMBER 34
FINE GRAINED SANDSTONE
SILTSTONE
CLAYSTONE
OIL SHALE (LOW TOC)
OIL SHALE
CANNEL SHALE
IMPURE COAL
COAL

Figure 13. Fence diagram illustrating the lateral transition of the McLeod seam from cannel shale near the basin center to coal toward the basin margins. Location of drillholes 0371 and P59A are illustrated on Fig. 10.

interpreted to be lacustrine delta deposits (Fig. 12). The central basin mudrocks with varve-like laminae are prodelta deposits that are transitional toward basin margins to delta front deposits that include the flaser- to lenticular-laminated siltstones and the ripple to horizontally stratified sandstones (Fig. 12). The delta front deposits interfinger toward basin margins with floodplain deposits (rooted mudrocks) and distributary channel deposits (cross-stratified sandstones) that accumulated on lacustrine delta plains. The coarsening upward mudrock and sandstone sequences interbedded with conglomerates, that occur directly adjacent basin margins, are also interpreted to be lacustrine delta deposits.

Stellarton Formation: Paleogeography

Figure 14 illustrates paleogeographic models of the Stellarton Basin during deposition of the Skinner Brook, Westville, Plymouth and Albion Members. When mires were not present, shallow lakes and a vegetated delta plain covered much of the basin floor (Fig. 14a). Lakes probably expanded seasonally over large areas of the basin and during these periods significant amounts of sediment entered the lakes. When the shallow lakes became infilled poorly drained swamps began to develop over much of the basin. Ultimately the swamps evolved to almost basin wide mires (Fig. 14b). Poorly drained swamps were maintained only near basin margins. A general lack of conglomerates suggests basin margin relief was relatively low during this period.

The paleogeography of the Stellarton Basin during deposition of the Coal Brook and Thorburn members was dominated by a perennial central basin lake (Fig. 15a and b). Mouth bar deltas built out longitudinally into the lake forming narrow delta plains (Fig. 15a). Rhythmically layered muds with varve-like laminae were deposited in central areas of the lake. During periods when sediment supply was restricted, mires developed on abandoned delta plains and algal-rich mud/oil shale accumulated in the lakes (Fig. 15b). Sufficient relief existed for alluvial fans to form adjacent basin margins, however they did not prograde far into the basin.

REGIONAL PALEOGEOGRAPHY

Before considering the parameters that controlled the development of Late Carboniferous mires in the Cumberland and Stellarton basins, it is useful to discuss regional paleogeograpy. This section describes how the Cumberland and Stellarton basin fit within the late Carboniferous paleogeography of the regional Maritimes Basin.

Cumberland Basin

During deposition of the Joggins and Springhill Mines Formations (Westphalian A to mid B) the Maritimes Basin region appears to have been largely uplifted. The exceptions were fault controlled valleys such as the Athol Syncline area of the Cumberland Basin. Evidence for the above includes: 1) a lack of Westphalian A-mid B strata throughout much of the Maritimes Basin (Fig. 2); 2) thick isolated sequences of Westphalian A to mid B strata in isolated depocenters adjacent major fault zones; 3) reworked Namurian spores throughout the Joggins and Springhill Mines Formations (Ryan *et al*, 1990) suggesting post Naumurian uplift. Thus during the Early Westphalian the Athol Syncline area appears to have been an intermontane valley bordered to the south and west by highlands and to the north and east by a broad uplifted platform that covered much of the Maritimes Basin.

Stellarton Basin

By the mid Westphalian B, sediment began to accumulate over large areas of the Maritimes Basin (Fig. 2). By the Westphalian C-D coal-bearing strata was being deposited throughout the Maritimes Basin (Fig. 2) (Hacquebard, 1986). This suggests that uplifted areas had largely disappeared either through denudation or infilling of fault valleys. With the exception of the Stellarton Basin, red beds were deposited over much of the extreme southern Maritimes Basin (e.g. Cumberland Basin area) during the Westphalian C-D (Fig. 2). During the same period predominantly grey coal-bearing sequences were deposited over the rest of

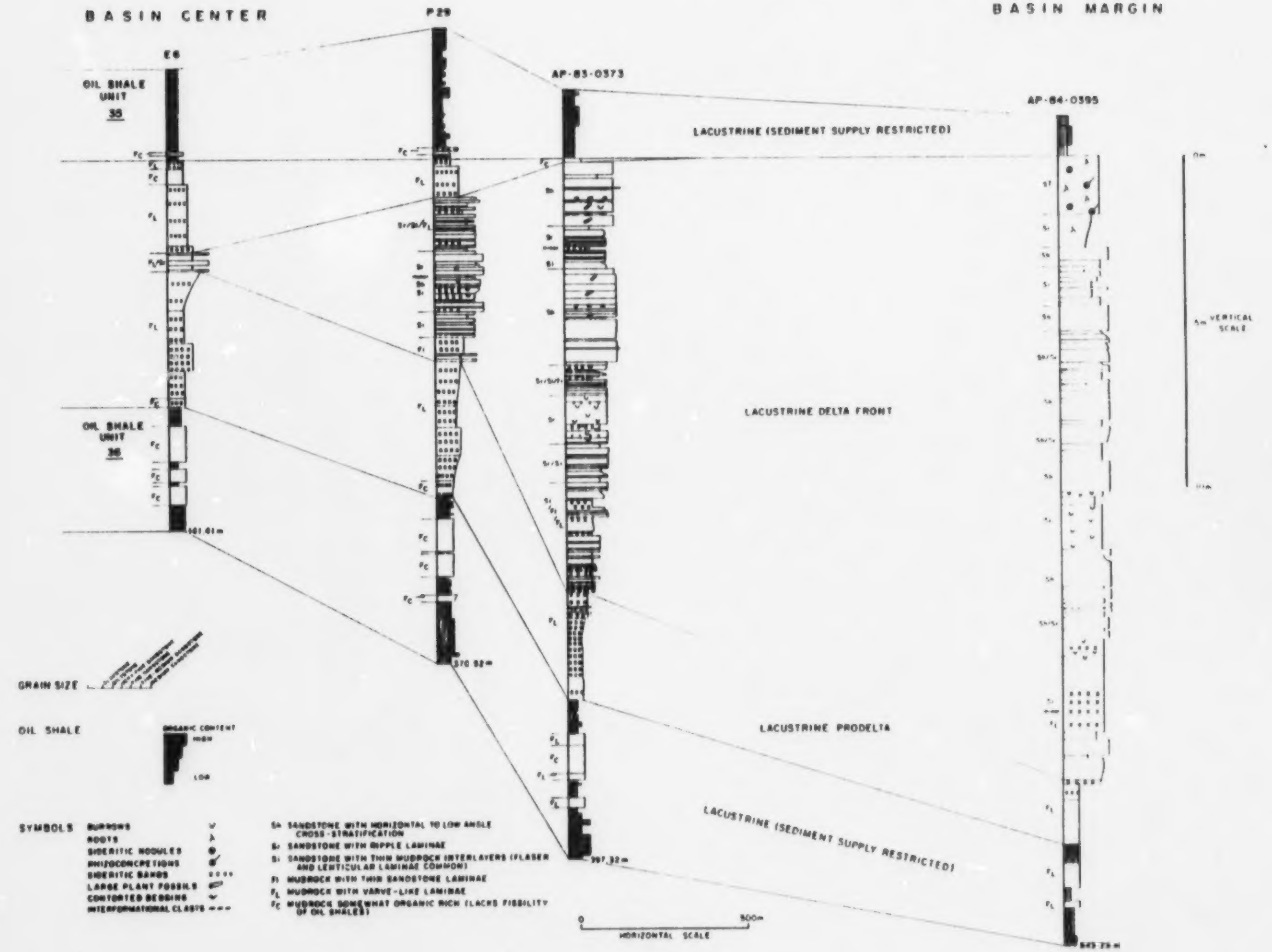
BASIN CENTER
BASIN MARGIN
E6
P29
AP-83-0373
AP-84-0395
OIL SHALE UNIT 35
OIL SHALE UNIT 36
LACUSTRINE (SEDIMENT SUPPLY RESTRICTED)
LACUSTRINE DELTA FRONT
LACUSTRINE PRODELTA
LACUSTRINE (SEDIMENT SUPPLY RESTRICTED)
370.92 m
397.32 m
5m VERTICAL SCALE
0
500m
HORIZONTAL SCALE
GRAIN SIZE
OIL SHALE
ORGANIC CONTENT
HIGH
LOW
SYMBOLS
BURROWS
ROOTS
SIDERITIC NODULES
RHIZOCONCRETIONS
SIDERITIC BANDS
LARGE PLANT FOSSILS
CONTORTED BEDDING
INTERFORMATIONAL CLASTS
Sh SANDSTONE WITH HORIZONTAL TO LOW ANGLE CROSS-STRATIFICATION
Sr SANDSTONE WITH RIPPLE LAMINAE
Si SANDSTONE WITH THIN MUDROCK INTERLAYERS (FLASER AND LENTICULAR LAMINAE COMMON)
Fl MUDROCK WITH THIN SANDSTONE LAMINAE
F_L MUDROCK WITH VARVE-LIKE LAMINAE
F_C MUDROCK SOMEWHAT ORGANIC RICH (LACKS FISSILITY OF OIL SHALES)

Figure 12. Stratigraphic section between oil shales 35 and 36 illustrating coarsening and thickening of lacustrine delta deposits toward basin margins. The location of holes [AP-84-0395 and E6] are shown on Fig. 10.

the Maritimes Basin (Hacquebard, 1986). This suggests that the southern Maritimes Basin was in an upland setting relative to northern areas. Therefore, from Westphalian C to early D, the Stellarton Basin was a rapidly subsiding fault controlled valley in an upland area of a broad alluvial plain.

CONTROLS ON DEVELOPMENT OF PALEOMIRES

Climate

Paleogeographic reconstruction by Scotese *et al.*, (1979) shows the Maritimes basin region occupying a near equatorial position during the Late Paleozoic. Equatorial climates vary from arid to humid depending on the regional geography. For example, peatlands in East Africa are largely confined to intermontane valleys of relatively high elevation because cooler temperatures at higher elevations restrict water evaporation (Thompson and Hamilton, 1983). The lack of a demonstrated marine influence within the Joggins and Springhill Mines Formation raises the possibility that the Athol Syncline area was sufficiently elevated during the Early Westphalian for a cooler, montane climate. D'Orsay and Van de Poll, (1985) proposed that micro textures on quartz grain surfaces from the Westphalian A Boss Point Formation (Fig. 4) were consistent with those of some recent glacial deposits. It has been suggested that the Westphalian A-B Cobequid and Caledonia highlands were of sufficient elevation to form rainshadows (Calder, 1991).

Carboniferous coals, with the exception of Gondwana coals, are commonly thought to have developed from forested mires that formed under humid tropical conditions. In contrast, red beds are generally attributed to dry climates or those with high seasonal fluctuations in rainfall. These concepts have been usefully applied to regional studies of some coal-bearing sequences (e.g. Bless *et al.*, 1981, Phillips *et al.*, 1985) however they may not always be applicable at the scale of a small intermontane coal basin. In both the Cumberland and Stellarton basins thick sections of red beds are in abrupt diachronous contact with thick grey coal-bearing sequences (Figs. 4 and 11). This occurs at a scale too small to be attributed to differences in climate within a basin.

The most wide-spread deposition of grey coal-bearing strata within the Athol Syncline of the Cumberland Basin occurred late in the depositional history of the Joggins Formation (Calder, 1991; Bromley and Calder, in press). The longest term deposition of grey coal-bearing strata, however, is represented by the Springhill Mines Formation, at the southern basin margin. Basin asymmetry with greatest subsidence at the southern basin margin, could explain localized, persistent wet conditions there, but seismic stratigraphy (Bromley and Calder, in press) may actually suggest the opposite. The persistence of wet conditions at the basin margin in the face of a regional trend to drier conditions has been attributed to groundwater discharge form alluvial fans. (Calder, 1991). Regionally drier conditions in the basin may be explained by long-term climate change, changes in the net subsidence, or both.

The mixed fluvial-lacustrine assemblage of the Joggins Formation intermixed with red beds at one and the same time suggests conditions that were at times wetter, at times drier, than the fluvial grey beds of the basin margin. Such periodic change or instability of groundwater levels, whatever their cause, were not well suited to lengthy peat formation, resulting in the thinner coals of the Joggins Formation.

Reddening of the Stellarton Formation adjacent basin margins has been attributed to well-drained conditions and slightly higher elevations relative to the basin center. Duricrusts within the red beds may indicate that significant water table fluctuations in response to seasonal variation in rainfall. The grey coal-bearing members of the Stellarton Formation also contain some evidence for seasonal and perhaps longer term fluctuations in rainfall; for example, microbanding of the coals. Numerous rooted horizons within Albion and Westville strata could also, in part, reflect climatic variation. The surface areas of the generally shallow Westville and Albion lakes may have changed significantly in response to seasonal and slightly longer term differences in rainfall. This may have allowed frequent colonization of lake deposits by plants that encouraged subsequent development of mires.

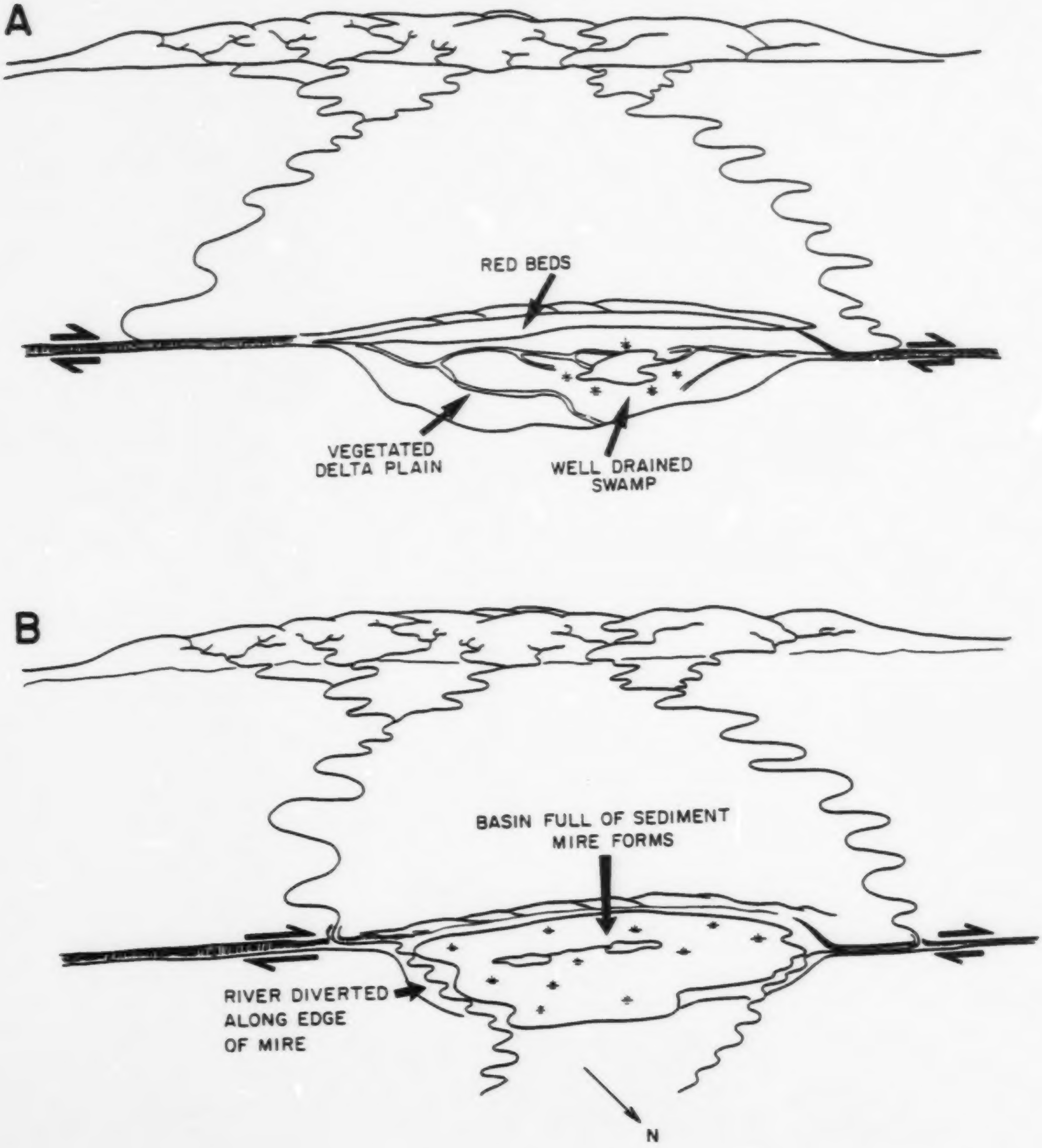
A
RED BEDS
VEGETATED DELTA PLAIN
WELL DRAINED SWAMP
B
BASIN FULL OF SEDIMENT
MIRE FORMS
RIVER DIVERTED
ALONG EDGE
OF MIRE
N

Figure 14. Paleogeographic models of the Stellarton Basin during deposition of the Skinner Brook, Westville, Plymouth and Albion Members.
(A) when no mires existed within the basin and sediment supply was relatively high.
(B) when a basin wide mire had developed and sediment supply to the basin was restricted.

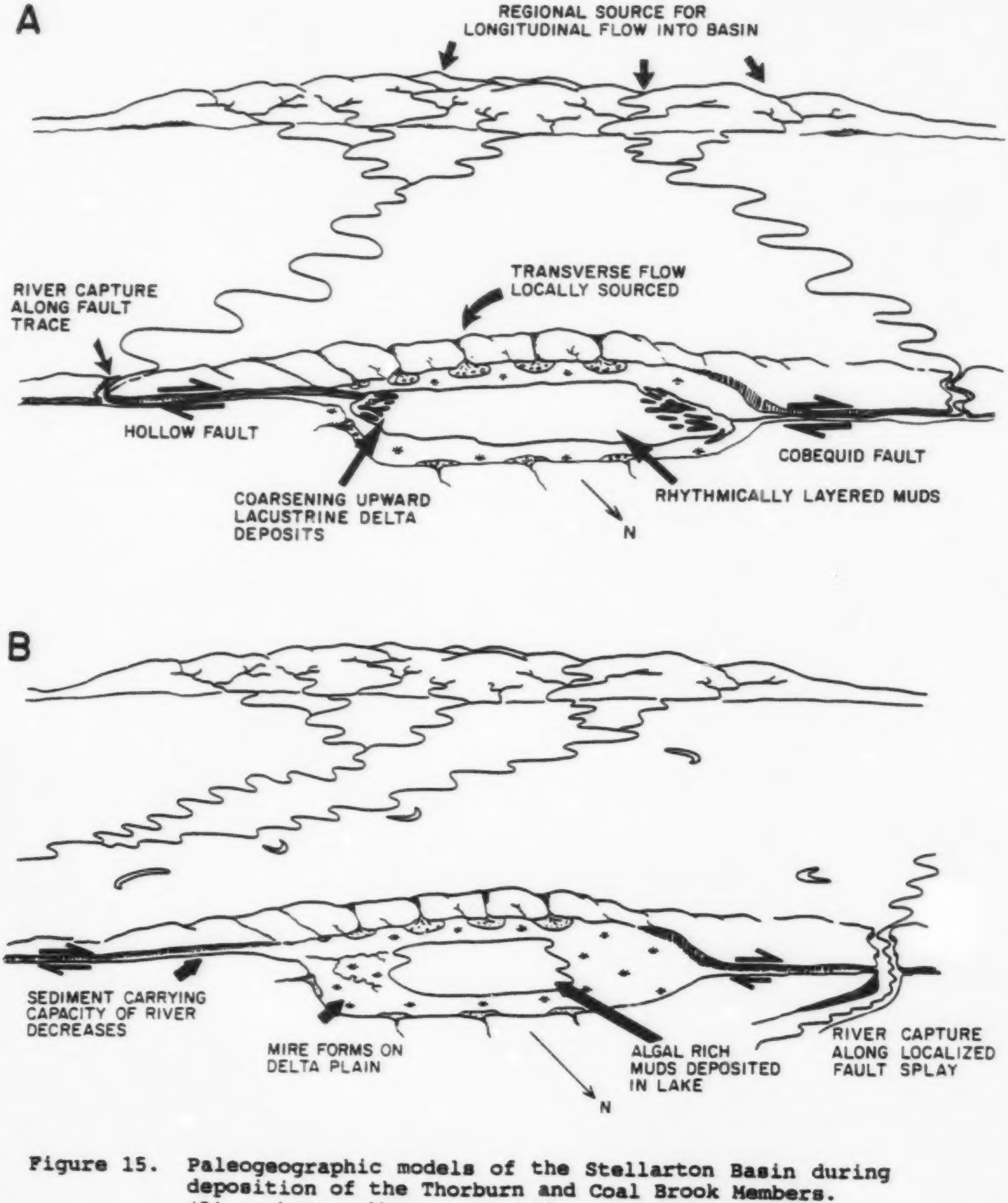
A
REGIONAL SOURCE FOR LONGITUDINAL FLOW INTO BASIN
TRANSVERSE FLOW LOCALLY SOURCED
RIVER CAPTURE ALONG FAULT TRACE
HOLLOW FAULT
COBEQUID FAULT
COARSENING UPWARD LACUSTRINE DELTA DEPOSITS
RHYTHMICALLY LAYERED MUDS
N
B
SEDIMENT CARRYING CAPACITY OF RIVER DECREASES
MIRE FORMS ON DELTA PLAIN
ALGAL RICH MUDS DEPOSITED IN LAKE
RIVER CAPTURE ALONG LOCALIZED FAULT SPLAY
N

Figure 15. Paleogeographic models of the Stellarton Basin during deposition of the Thorburn and Coal Brook Members.
(A) when sediment was being supplied to the basin and mouth bar deltas were building into a central basin lake.
(B) when sediment supply was restricted and mires were forming on an abandoned delta plain.

Varve-like laminae similar to those within the prodelta mudrocks of the Coal Brook and Thorburn Members have been linked to seasonal variation in rainfall and subsequent water discharge into lakes (eg. Lambert and Hsük, 1979). The surface area of the deeper Coal Brook and Thorburn lakes would not have changed as readily in response to rainfall variations. This may explain in part why mires managed to develop adjacent to Coal Brook and Thorburn lakes.

The switch from shallow Westville-Albion lakes to deeper Thorburn-Coal Brook lakes could reflect an overall increase in rainfall. This possibility is not discounted, although other controlling factors other are suggested below.

Basin Hydrology

Both basins appear to have been hydrologically open systems during deposition of their coal measures. In the Cumberland Basin, during deposition of the Springhill Mines Formation, through-flowing river systems were probably very efficient at carrying water into and out of the basin. During deposition of the Joggins Formation lakes and less well developed fluvial systems would not have provided as efficient drainage. Major through flowing river systems rarely, if ever, existed within the Stellarton Basin. Instead, drainage was probably largely into and out of lakes, swamps and mires. Although this may have been relatively inefficient, carbonates are virtually absent and no evaporites occur within the Stellarton Formation indicating, sediment accumulated in hydrologically open lakes.

Open drainage systems allow a quick return to equilibrium conditions following floods, as excess water can be carried quickly out of the basin. This maintains a general balance between water inflow and outflow that results in a stable water table. A stable water table is favourable for mire growth if peat accumulation is able to keep pace with tectonic and compaction subsidence.

Subsidence and Sediment Supply

Approximately 2000 metres of compacted coal-bearing strata (Joggins and Springhill Mines Formations) accumulated in the Athol Syncline area of the Cumberland Basin from mid-Westphalian A to mid-Westphalian B. Lippolt and Hess, (1985) have estimated the Westphalian A and B to represent a total of 4 million years. Assuming the period from mid-Westphalian A to mid-Westphalian B represents 2 million years subsidence rates within the Athol syncline area, during deposition of the Joggins and Springhill Mines Formations, would have been 1.0m/1000 years. The average peat accumulation rate in modern tropical mires is approximately 2.0m/1000 years (Calder, 1991). If this is broadly comparable to Carboniferous mires, average peat accumulation rates would have exceeded average subsidence rates in both the Cumberland and Stellarton basins. (See discussion below.)

Although basin subsidence rates were high, there is a much greater percentage of fluvial compared to lacustrine deposits within the Joggins and Springhill Mines Formation. This indicates that sedimentation rates were usually high enough to keep the basin floor from subsiding below the water table for extended periods of time.

Subsidence and sediment accumulation rates appear to have varied during deposition of the Joggins and Springhill Mines Formations. During deposition of the Little River Member of the Joggins Formation large volumes of Polly Brook Formation conglomerates were shed northward of the Cobequid highlands. This indicates that basin subsidence rates during this period were relatively low (cf Blair, 1987; Blair and Biloudeau, 1988). The abrupt contact between the Little River Member and the underlying Boss Point Formation (predominately channel sandstones) (Fig. 4) suggests that a regional source of sandy sediment was shut off. In the absence of a regional sediment source erosion of the Cobequid highlands would have supplied the majority of the sediment to the Athol Syncline area.

The widespread wet conditions in the basin during deposition of the Coal Mine Point Member of the Joggins Formation suggests a lower ratio of sediment accumulation to subsidence. The gradual upsection retreat of the Polly Brook Formation (Fig. 4) suggests that less sediment was available from local sources.

Sediment supply from regional sources was apparently not sufficient to maintain major fluvial systems throughout the basin (Fig. 6). This would have meant that wet areas were available for mires to develop free from sediment contamination.

The higher percentage overall of red beds and fluvial deposits within the Springhill Mines Formation indicate drier conditions and a higher ratio of sediment accumulation to subsidence. The thickest and lowest ash coals within the Cumberland Basin formed adjacent the basin margin during this period. This suggests that basin margin areas had low sediment supply rates indicating that almost all sediment within the basin was from regional sources. The splitting of coals of the Springhill Mines Formation (Coal Mine Brook Member) basinward around fluvial deposits indicates that mires and regionally sourced fluvial systems coexisted within the Cumberland Basin. The timing of autocyclic processes such as river avulsion and channel belt migration would have controlled how long mires would have existed without significant sediment contamination.

Subsidence rates within the Stellarton Basin were, on average, also very high. The Westphalian C through early D encompassed a period of approximately 4.5 million years. (Lippolt and Hess, 1986). Calculated on the basis of 2600m of compacted basin-fill this would suggest an average subsidence rate for the Stellarton Basin of 0.60 meters/1000 years.

It is unlikely local erosion would have provided sufficient sediment to produce 2600m of basin-fill within the Stellarton Basin. This suggests that sediment supply to the Stellarton Basin was probably for the most part regionally sourced. Gibling *et al.*, 1992 suggested that northeasterly flowing rivers, perhaps sourced as far away as the Central Appalachians, carried large amounts of sediment into the Maritimes Basin during the late Westphalian. River capture along the east-west trending Hollow and Cobequid fault traces probably directed these northeasterly flowing rivers longitudinally into the Stellarton Basin (Fig. 15a). Sediment disperal patterns supports this indicating major sediment input at both the east and west ends of the basin (Naylor *et al.*, 1989). Mires would probably only have developed within the relatively small Stellarton Basin when the regional sediment supply became restricted.

The predominance of lacustrine deposits, within the Stellarton Formation, suggests sediment accumulation rates, within the Stellarton Basin, were generally much too low to keep pace with subsidence rates. Changes in sediment accumulation and subsidence rates in the Stellarton Basin were also important controls on mire development. During deposition of the Albion and Westville Members the ratio of sediment accumulation to subsidence appears to have been highest. Lakes that developed within the basin were infilled and mires developed over much of the basin floor. The thick coals of the Albion and Westville members suggest that sediment supply was not sufficient to hinder mire growth. This may suggest that slower subsidence rates were the dominant control on development of thick laterally extensive mires within the Stellarton Basin.

The presence of a perennial central basin lake during deposition of the Thorburn and Coal Brook members indicates a low ratio of sediment accumulation to subsidence. The thick lacustrine delta sequences of the Thorburn and Coal Brook members suggest that sediment supply to the basin had probably not slowed significantly relative to Westville Albion time. This indicates that high rates of basin subsidence may have kept much of the basin floor below the water table and limited mire development to near basin margins.

Groundwater discharge from alluvial fans

In the Cumberland Basin the gradual southward change from red beds, to grey beds within the Springhill Mines Formation indicate that much wetter conditions prevailed near the southern basin margin. Calder, (1991) concluded that groundwater discharge from alluvial fans kept basin margin areas wetter and supplied the rheotrophic mires of the Springhill Mines Formation with a supplemental water source. Such groundwater recharge in modern settings is crucial to the maintenance of wetlands in drier periods. This led Calder to infer that the climate may not have been sufficiently humid for the development of solely rain-fed mires.

Mires of the Joggins Formation may also have been influenced by groundwater discharge from alluvial fans. Wetter conditions on average during deposition of the Joggins Formation may mean that groundwater discharge from alluvial fans actually contributed to drowning of mires. The alluvial fans of the Stellarton Basin were probably not well enough developed to have influenced local water levels within the basin.

SUMMARY AND CONCLUSIONS

The Cumberland Basin (Athol Syncline area) and the Stellarton Basin were both rapidly subsiding Late Carboniferous depocenters within the regional Maritime Basin. Despite their close proximity and similar tectonic setting significant differences exist between their coal bearing basin-fill. The coals of the Cumberland Basin are found interbedded with both fluvial-lacustrine deposits (Joggins Formation) and predominately fluvial deposits (Springhill Mines Formation). The coals of the Stellarton Basin are contained within the predominately lacustrine Stellarton Formation.

Although ombrotrophic, solely rain-fed mires have been favoured as precursors of many Carboniferous coals (Moore 1987, among others) the coals of both the Cumberland and Stellarton Basins apparently formed from rheotrophic or flow fed mires. It is inferred, therefore, that the development of mires in each basin depended on the stability and position of the water table. Both basins were hydrologically open so that peak periods of water inflow would have been eventually balanced by outflow. This means that mires would not have been easily drowned simply by an increase in rainfall. The long term position of the basin floor relative to the water table in each basin was primarily a function of the rate of basin subsidence and sediment supply. If higher rates of subsidence were not balanced by an increase in sediment supply, the floor of each basin was lowered relative to the water table and conditions became wetter.

Overall subsidence rates in both basins were high, but the Stellarton Basin appears to have subsided at only a little over half the rate of the Cumberland Basin. Despite a slower average subsidence rate lacustrine conditions predominated in the Stellarton Basin. This suggests that sediment supply to the Stellarton Basin was commonly insufficient to infill lakes and thus raise the level of the basin floor above the water table. The thick coals and oil shales of the Stellarton Basin may reflect prolonged periods with little sediment input to the basin.

In contrast, even though the Cumberland Basin subsided more quickly than the Stellarton Basin, its coal measures contain more red beds and fewer lacustrine deposits. This suggests that sediment supply was sufficient to keep pace with subsidence and that the basin floor was rarely below the water table for prolonged periods. The high subsidence and sediment supply rates within the Cumberland Basin would have made mires vulnerable to burial if environmental factors such as climate change slowed peat accumulation rates. This may explain why the coals of the Cumberland basin are much thinner on average than the coals of the Stellarton Basin.

The explanation for higher rates of sediment supply within the Cumberland basin could be that both local and regional sediment sources supplied the basin. Significant amounts of sediment would have been contributed locally from the Cobequid and Caledonia Highlands. In addition the Cumberland Basin is parallel to the predominate late Carboniferous sediment dispersal trend within the Maritimes Basin. This would have encourage regional drainage into the basin. In contrast rivers that were flowing down the regional paleoslope had to be diverted into the Stellarton Basin (Figs. 14a and 15a).

Both the Cumberland and Stellarton Basins would have acted as local base levels for rivers that flowed into them. In the case of the Stellarton Basin through-flowing river systems apparently never developed, possibly indicating that the basin floor had a very low slope. This would have sharply reduced the sediment carrying capacity of in-flowing rivers. Unless the basin floor subsided rapidly enough to continually accommodate deposits of large amounts of sandy sediment near basin margins, river systems would have backed up with sediments. This would have restricted sediment supply to the basin and allowed mires to develop.

A clearer understanding of the controls on development of paleomires within the Cumberland and Stellarton basins provides some interesting insights on coal exploration possibilities in similar basins. The apparent reliance of mires of the Springhill Mines Formation upon groundwater discharge from alluvial fans suggests that basin margin areas with thick conglomerates, especially in transcurrent settings, should not be overlooked as possible coal exploration targets. Similarly, basin margin areas in intermontane basins, with thick central basin lacustrine sequences, also offer coal exploration possibilities. Finally, it may be possible to trace red bed sequences in some intermontane coal basins laterally into sequences with thick coals.

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NOTES

PETROGRAPHIC EXAMINATION OF COAL LITHOTYPE SAMPLES FROM THE LOWER CRETACEOUS GATES FORMATION: A COMPARISON OF AUTOMATED IMAGE ANALYSIS VERSUS MANUAL MICROSCOPY

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Coal lithotype samples from the Lower Cretaceous Gates Formation were analyzed petrographically using a Kontron image analyzer equipped with a microscope, television camera and motorized stage. Previously the same sample set had been analyzed using conventional point counting methods, and results of that study were used to assess vertical in seam variations in respect to peat forming environments (Marchioni and Kalkreuth, 1991). Comparison of coal lithotype versus vitrinite content are in good agreement using either method. There is considerable overlap in vitrinite contents between lithotypes in both methods however average results show that vitrinite content increases with brightness of the lithotypes. Both the overlap and the increase in vitrinite content are considered normal on the basis of lithotype definition. In vertical section, vitrinite content in automated and manual methods compare favourable to each other and show good correlation with lithotype columns. Use of the reflectance histogram to compare lithotype maceral group content is shown. By normalizing population sizes, 'average' histograms can be developed using the data obtained form all samples of each lithotype. Plots of this averaged data can be considered as type histrograms and graphically depict the increase of vitrinite content with overall lithotype brightness. The results presented here indicate that image analysis of seam profiles is a fast and reliable method to determine gross petrographic composition of coal seams. Variations and trends in petrographic composition as determined by image analysis will aid in the understanding of seam development and can also be used to assess depositional environments and utilization potentials.

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NOTES

COAL COMPILATION PROJECT; GEOSCIENCE INFORMATION SYSTEM (GSIS) SUPPORTED COAL RESOURCE MAPPING IN ALBERTA

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ABSTRACT

The objective of the Coal Compilation Project (CCP) is to provide coal resource maps to stimulate and support industry exploration programs, and assist government in matters of resource management. An essential feature of the program is the use of cost effective Geoscience Information System (GSIS) technology that allows the database and various thematic maps to be analyzed, updated, and displayed with complete flexibility at any scale.

The CCP is scheduled to have sixteen 1: 50 000 scale map sheets completed over a three year period. Each map is designed to be a stand alone, unique product contributing to an overall synthesis of information. Maps generated are at a regional or reconnaissance level. Collection of new data is limited. Data compiled and evaluated are based on Alberta and Federal government sources and unpublished corporate reports and data from the coal industry.

In 1989-90, the CCP focussed on the Hinton - Grande Cache Corridor, located in west-central Alberta, and included four contiguous NTS map sheets. From southeast to northwest, they are; 83F/5, 83E/9, 83E/14, and 83E/15. For each map sheet, a product has been generated that includes a coal resource map (scale 1: 50 000), thematic 'snapshot' maps (scale 1:250 000), and accompanying text. During the first year of the CCP, substantial time was spent in developing the hardcopy product template, and in designing the GIS template. Some minor field checking, sampling, and analysis are done during each year to provide quality control and further support coal quality research. During, 1990-91, the second year of the project, focus was on the area north of Grande Cache (83L/2, 83L/3, 83L/7, and 83L/10). An additional map, 83E/16, located east of Grande Cache, and in the Berland River area was completed. Six maps are being worked on during 1991 - 92, four maps (83F/4, 83C/9, 83C/15 and 83L/16) continue the coverage south from Hinton and two maps are in the Crowsnest Pass area (82G/8 and 82G/9).

PROJECT OBJECTIVE

The objective of the pilot Regional Coal Compilation Project (CCP) is to provide coal resource maps to stimulate and support industry exploration programs, and assist government in matters of resource management. An essential feature of the program is the use of cost effective Geoscience Information System (GSIS) technology that allows the data base and various thematic maps to be analyzed, updated, and displayed with complete flexibility at any scale.

BACKGROUND

The idea for a new coal geology map series came from a 1986 project on the Status of Coal Geology Work in Alberta (Langenberg et al., 1986), which included a questionnaire that was sent to various Alberta industries and government agencies both in the United States and Canada. The Alberta Industry identified the dated nature of coal geology maps in Alberta and the complete lack of maps in some areas. Many coal maps in the foothills area at 1:63 360 scale were produced pre 1950. In the Wapiti area with the most recent map is from 1946 (Allan and Carr, 1946). New mapping by the Alberta Geological Survey (AGS) has been almost entirely in the plains area of Alberta.

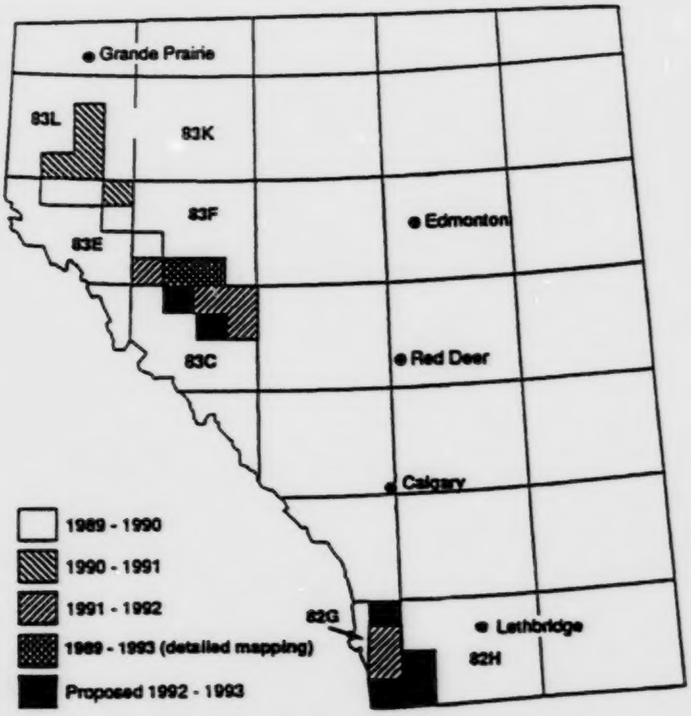
Grande Prairie
83L
83K
83F
Edmonton
83E
83C
Red Deer
Calgary
82G
Lethbridge
82H
1989 - 1990
1990 - 1991
1991 - 1992
1989 - 1993 (detailed mapping)
Proposed 1992 - 1993

Figure 1. Coal mapping program; CCP mapping includes all areas except that identified as detailed mapping.

In the mid-1980's computer mapping techniques had become common and was implemented as the modus operandi at the AGS. That approach and the availability of Geographic Information System (GIS) technology provided the conditions necessary to produce maps that reflected available information in a flexible and cost effective manner. The principal strategy was to produce a number of maps in a designated time frame where costs would be far less than traditional mapping procedures.

The concept was tested during database development at AGS (Richardson et al., 1989a) and during a pilot Geoscience Information System (GSIS) project where GIS mapping technology was experimentally tested for a area centred on the Highvale mine (Richardson et al., 1989b). A Technical Advisory Committee for the coal program at AGS supported the concept and an initial 3 year project with an 16 map objective (5% of possible coal maps in Alberta) was initiated in the 1989-90 fiscal year. To date nine 1:50 000 maps have been published and six more are in progress (Figure 1).

CHALLENGES

The use of GIS technology and the focus on data compilation with only minimal field work, in opposition to traditional field work and data gathering, was a totally new and untried concept. Much more data than expected was found in industry and government files. The data had been collected over a large number of years and at different levels of precision and for a wide variety of purposes. Virtually none of the data was in a electronic format and those data had not been collected with the specifications of modern databases in mind. In addition, some conflicting data was found. Limited field time and difficult foothills terrain only allowed limited field checking. Staff training was required during the first two years of the program. In the early stages of the program, GIS platform limitations (hardware/software/connectivity) provided additional non-geological technical challenges.

METHODOLOGY

Each year a number of map areas are selected by the Coal Program Technical Advisory Committee at a special meeting to set priorities. Once areas are identified, data gathering begins with a literature search and identification of possible sources of information. AGS reports, internal files, and electronic database provide a primary level of information. The Energy Resources Conservation Board (ERCB) is a major source of information for both coal and coal related oil and gas information. Much of the underpinning geologic information used in the CCP maps comes from mapping by the Geological Survey of Canada. Information fundamental to the effectiveness of the CCP maps comes from industry reports and files. Every effort is made to acquire information from industry and to incorporate it in the CCP maps and reports in a way that does not compromise company confidentiality.

A minor level of data gathering and spot checking in the field is done for each map area. Spot checks are accomplished strictly by truck and helicopter to adhere to tight schedules and limited budgets.

Available geologic data, digital map data from Alberta Forestry Lands and Wildlife Department and direct digitization of map information are input and formatted within a GIS to create a base map.

When Geologic information is combined with base map information within a GIS, and product generation begins. During the first year of the CCP, substantial time was spent in developing the hardcopy product template, and in designing the GIS template. For each map sheet, a product has been generated that includes a coal resource map (scale 1: 50 000), thematic 'snapshot' maps (scale 1: 250 000), and accompanying text. The snapshot maps comprise such information as coal exploration data, index to specific reference documents, coal dispositions and coal development potential. Each map has its own legend to avoid confusion.

GIS MODELLING (COAL RESOURCE DEVELOPMENT POTENTIAL)

The analytical power of GIS coal resource modelling has not been explored to any depth because the project focuses on producing new maps as rapidly as possible. However, since the information is stored within a fully functional GIS, all the modelling capabilities (discussion beyond the scope of this paper) are present for the future.

One application of GIS technology has been employed to produce a simple evaluation of Coal Resource Development Potential. The model is a semiquantitative and subjective evaluation of the potential of coal development in a map area based on limited data. It is mainly based on geological criteria and does not take into account governmental restrictions on coal development. Neither does the model evaluate actual economic constraints to development now or in the future.

The coal development potential was based on three main criteria:

1. COAL PRESENCE

a. Resources

The amount of data is generally too small for a quantitative evaluation of coal resources except in those limited areas with drilling. When drilling has been done the area could be ranked high.

b. Coal Quality

Very little coal quality data is available but where test results are present the potential of the coal for development is strengthened. In general where a sample has been collected and analyzed the coal has an inherent development potential.

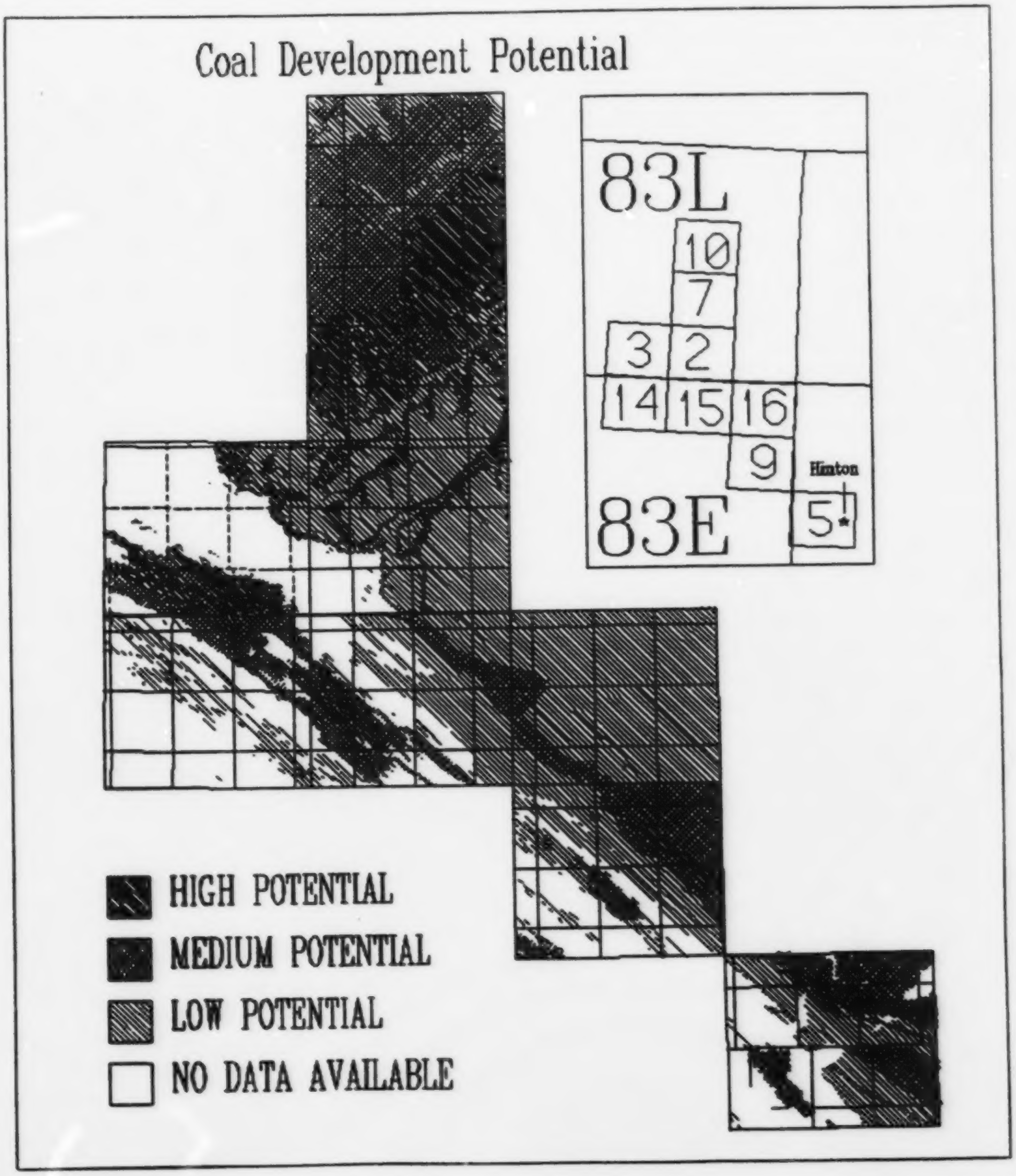
Coal Development Potential
83L
10
7
3
2
14
15
16
9
Hinton
83E
5
HIGH POTENTIAL
MEDIUM POTENTIAL
LOW POTENTIAL
NO DATA AVAILABLE

Figure 2. Coal Development Potential Model.

2. MINING POTENTIAL

a. Overburden

An evaluation of overburden for surface mining and depth for underground mining has been made. (The 'Mining Potential' criteria did not take into account governmental restrictions on coal development or the evaluation of economics.)

b. Geotechnical

Geotechnical considerations included an evaluation of structural setting, both simple and complex, with the possibility of structurally thickened seams. Consideration was given to infrastructural concerns related to site, environment and potential mining problems.

3. DATA AVAILABILITY

Relatively little coal data is generally available for most map's areas but where present the potential of the coal for development is strengthened. In general, where an outcrop, adit, drillhole, trench or sample is present the coal has an increased development potential. Some value was given to areas containing sediments that typically include coal. Areas in green on the thematic inset 'Coal Development Potential' snapshot map reflect higher level of knowledge and potential for development of coal than the blue (medium) or red areas (low). Blue areas indicate more information is needed to determine the coal development potential. Red areas indicate some potential for development. The remaining uncolored areas have no data available mainly because the coal, if present, is at depth under non-coal-bearing rocks. The composite map (Figure 2) shows the Coal Development Potential of the nine areas studied to date.(On the black and white Figure 2, green is shown as a heavy crosshatch, blue as a medium crosshatch, and red as a light crosshatch.)

PROJECT BENEFITS

BENEFITS FOR EXPLORATIONISTS

In just two years nine 1:50 000 maps have been published and six more are in progress and have a spring 1992 delivery date. The maps compile the sort of information that would provide a starting point for explorationists. Having information, gathered from a wide spectrum of sources, greatly reduces the risk of duplication of effort. Since the information is in digital form and within a GIS the explorationist also has the option to use the unique and powerful analysis capability of the software. Lastly the project provides for the archiving of selected corporate and scientific coal data that may have otherwise been discarded. A list of some of the data and reports volunteered to the AGS by industry is listed in Table 1. While it is very difficult to put a value on this data, one can estimate the replacement cost (in 1992 $); our estimated replacement cost is approximately $40 million.

TABLE 1. A tabulation of the corporate coal data volunteered to the AGS.

DATE	COMPANY/INDIVIDUAL	CONTRIBUTION	1992 REPLACEMENT COST ($\$10^3$)
1989-06-14	UNOCAL Canada Limitec	5geological assessment rpts for coal projects in the Ab Mtns/Foothills	1660
1989-07-12	Denison Mines Limited	selected maps and figures from 3 project areas in the Ab Mtns/Foothills	250
1990-01	Manalta Coal Ltd.	geological assessment rpt for the Kakwa area (in the Ab Mtns/Foothills)	70
1990-01-18	UNOCAL Canada Limited	geological assessment rpt for the Sterne Crk area (in the Ab Mtns/Foothills)	200
1990-08-13	D. MacFarlane	2 geological assessment rpts for the Copton area (in the Ab Mtns/Foothills Region)	10000
1990-09-11	ESSO Resources Canada Limited	misc maps, data and reports from the Smoky River area of Ab	490
1990-11-26	ESSO Resources Canada Limited	geophysical log tapes (200+) for a number of ESSO coal project areas in Ab	830
1990-12-17	ESSO Resources Canada Limited	misc maps, data and reports from coal projects in NW Ab	300
1991-01-21	ESSO Resources Canada Limited	misc raw exploration data and original mylar maps/drwgs from coal projects in Ab (13 boxes of mtl)	850
1991-05-31	UNOCAL Canada Limited	geological assessment rpts from 6 coal projects areas in the Ab Mtns/Foothills	1500
		sample cuttings' trays /vials from 4 Ab coal programs	150
		misc raw exploration data and original mylar maps /drwgs from coal projects in Ab (1 box of mtl)	50
1991-06-17	ESSO Resources Canada Limited	misc coal samples, & coal exploration data & reports from coal projects in Ab (40 boxes of mtl)	20000
1991-06-28	Crows Nest Resources Limited	geological assessment rpt for the Bryan Mtn area (in the Ab Foothills)	1100
1991-08-16	Crows Nest Resources Limited	geological assessment rpts for the Ardrossan, Cooking Lake and Fox Creek project areas (in the Ab Plains)	2800
1991-12-04	JAYCON RECONNAISSANCE Field Sampling Consultants	rpt re: 'Quality of Deep Coals in the Alberta Plains'	150
		TOTAL *(1992 $\$10^3$)*:	$40000

PROJECT BENEFITS FOR RESOURCE PLANNERS AND MANAGERS

Resource planners and managers are seldom specialists in coal and often have a very broad and general background. They need to be able to access uncomplicated summary information. In most areas of Alberta coal resource potential is poorly established particularly when compared to forestry or wildlife resources. Knowledge about all available resources is necessary for planning and formulation of policy. The availability of the CCP maps help to avoid resource conflict by identifying areas with coal, even in areas where data is sparse. Similarly the maps and data can be used to avoid environmental conflicts by using the overlay and analytical capabilities of the GIS.

CONCLUSION

The Regional Coal Compilation Project has been successful in meeting its objectives by providing maps reports and data within a powerful new technology in a timely and cost effective manner.

ACKNOWLEDGEMENTS

The project was funded by the Alberta Department of Energy and the Alberta Research Council. The Alberta Geological Survey Coal Program Technical Advisory Sub-Committee provided valuable guidance for the project. Data compiled and evaluated has been based on the following principal sources: Alberta Research Council/Alberta Geological Survey (ARC/AGS), Energy Resources Conservation Board (ERCB), Geological Survey of Canada (GSC/ISPG), and information from the coal industry sector. Industry has cooperated and supported the CCP by providing unpublished corporate reports and data to the AGS. The availability of this information has been an essential component toward the success of this project. Roy Eccles is thanked for his comments and suggestions that improved this paper.

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COAL GEOSCIENCE PROGRAM
ALBERTA GEOLOGICAL SURVEY

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The objective of the Coal Geology Program at the Alberta Geological survey is to provide coal resource information to stimulate and support Alberta's energy industry and assist government in matters of resource management. New information is collected in the field or derived from existing sources of information. An essential feature of the program is the use of cost effective Geoscience Information System (GSIS) technology that allows the data to be archived, analyzed, updated, and displayed or reported in a wide variety of formats.

The program currently has three major components:

(i) The Coal Geoscience component involves the archiving, reporting and display of data through the maintenance of a coal geology data base and through use of a Geographic Information System.
(ii) The Coal Survey component involves collection and analysis, updating of data through both detailed and compilation mapping and coal quality analysis.
(iii) The third component is the new initiative in coal bed methane research.

The main deliverables are:

(i) The electronic data base* is available and used by industry, government departments and by internal ARC projects.
(ii) Coal geology maps (5 to 6 produced each year) are used by both industry and government departments and are in strong demand*.
*(Industry has provided large volumes of data to support the mapping and data archiving projects).
(iii) A major project, funded by 14 companies one Provincial and one Federal government departments, on a regional evaluation of Coal Bed Methane potential has been recently completed. A new Research Cooperative is being formed.

NOTES

METHANE RESOURCE POTENTIAL AND COAL WASHABILITY AT THE TELKWA COAL DEPOSIT

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Over 300 core holes have been drilled at Telkwa; most of the coal intersected in these holes was analyzed raw and washed for a range of properties. These analyses provide the basis for a random access database of over 3000 lines of information, each line representing a number of analyses of a single sample. Software including the QUIKMap GIS package and the Geoeas geostatistics package, as well as a number of in-house data handling programs are used to analyze the lateral variability of seam by seam washability and the methane resource at Telkwa.

Seam washability is estimated from drill core data, providing a database of estimates covering most of the Telkwa deposit. These data are kriged, gridded, contoured and displayed using QUIKMap. The spatial variability of coal washability by seam provides important information for mine planning and for assessing the representativeness of a limited number of test pit bulk samples.

The potential methane resource of a coal seam can be estimated using depth and coal quality data. The quality and stratigraphic data bases are used, in conjunction with two methods of calculating adsorbed methane, to illustrate the potential methane resource in the Telkwa Coalfield.

NOTES

POTENTIAL COKE STRENGTH AFTER REACTION OF BRITISH COLUMBIAN COALS

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Coke strength after reaction is an important measure of coke quality especially at a time when the coke (kilogram)/hot metal(ton) ratio is being decreased by the use of pulverized coal injection (PCI).

A sensitivity analysis using an empirical equation that predicts CSR values allows for a better understanding of the relative importance of ash content, base-acid ratio, rank and fluidity in influencing the resultant CSR. The base-acid ratio of the coal is one of the most important coal properties effecting the CSR of the resultant coke.

Often variations in BAR are correlated with variations in iron oxide concentration. Correlation and normative analysis helps to identify the mineral phase responsible for this variation. It often apppears to be pyrite or an iron carbonate. This could be confirmed using low temperature ashing. Identification of the mineral resonsible for changes in CSR may lead to ways of selecting or washing run-of-mine coal for improved CSR. Online ash analyzers in coal wash plants may be able to measure changes in iron content and therefore help in online quality control.

Estimated values of CSR for coal from the major coal-bearing formations in British Columbia are good to excellent. British Columbian coals are fortunate; they generally have base-acid ratios which are lower than the competitor coals in the rest of Canada and in U.S.A. This is an important advantage that should help improve the marketability of British Columbia coals.

NOTES

RARE EARTH ELEMENT PATTERNS IN WESTERN CANADIAN COALS

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ABSTRACT

Rare earth elements (REE) were determined in seven western Canadian coals using instrumental neutron activation analysis. The coals represent an age series from Lower Cretaceous to Eocene, and are from three tectonic belts, Insular (Suquash, Comox, and Nanaimo), Intermontane (Tulameen and Hat Creek), and Northeast Rocky Mountain (Quintette, and Bullmoose). Rank ranges from lignite-subbituminous B C (Hat Creek) to medium-volatile bituminous (Quintette and Bullmoose).

Concentrations of REEs are highest in Quintette (e.g. 32.3ppm Ce) and Suquash (e.g. 0.47ppm Lu) coals, and lowest in the Nanaimo (e.g. 8.7ppm Ce, and 0.11ppm Lu) and Comox coals. Chondrite-normalised patterns for all coals examined show enrichment of the LREE compared with HREE. In addition, an Eu anomaly occurs in all but the Nanaimo and Comox deposits. Shale-normalised patterns are generally relatively flat, i.e., REE in coals are undifferentiated with respect to shale; however, the Insular Belt coals exhibit HREE enrichments. High correlation coefficients with ash constituents in the coal indicate that the REE are associated with clay minerals, heavy minerals, and calcite. Preferential occurrence of the HREE or LREE in different mineral phases occurs in the Comox and Tulameen deposits. Vertical distributions of the REE primarily reflect variations in ash content of the coal-bearing sections. Significant exceptions, where certain of the REE are relatively more or less enriched in specific stratigraphic intervals, might potentially be useful for correlation purposes. In the Tulameen deposit the LREE are progressively more depleted towards the base of the section, both in coal and interbedded shale.

REE concentrations in the coals examined do not reflect age or rank of the deposits. Rather, source rock variations, modified by weathering, and depositional/diagenetic histories of the deposits, are thought to control the REE variations observed.

INTRODUCTION

The behaviour of REE's in sedimentary rocks and the surficial environment has been examined by, for example, Piper (1974) and Fleet (1984). Haskin et al. (1968) provided average REE values for North American shales. Earliest analyses of REE in coal were carried out by Goldschmidt and Peters in 1933. Subsequent studies have examined rare earth element abundances in coals, coal ash, and coal concentrates, for example, from the United States (Dawson and Siefert, 1986; Finkelman, 1980; Gluskoter et al., 1977; and Lyons et al., 1989), Bulgaria (Eskenazy, 1987a and 1987b), England (Lyons et al., 1989), Australia (Lyons et al., 1989), and Canada (Goodarzi and Van der Flier-Keller, 1988, 1989). Data based on comparisons with shales indicate that the REE are primarily associated with the inorganic fraction in the majority of these coals. Some authors argue that the REE may have been associated with the organic plant fraction at some point in the history of the coal, but have since been mobilised and become associated with clay minerals or epigenetic phosphates. The main controls on REE occurrence and distribution appear to be source rocks and weathering history (e.g. Lyons et al., 1989). The purpose of this paper is to provide information on the REE from seven coal deposits in western Canada, and to examine the occurrence, fractionation, and controls on the REE in these deposits.

METHODS

Samples were collected from seven coal deposits in western Canada representing three different tectonic settings and three ages (Table 1). Summaries of deposit geology may be found in Goodarzi and Van der Flier-Keller (1989 and 1988; Tulameen and Hat Creek, respectively), Van der Flier-Keller and Goodarzi (1991; Insular Belt deposits), and Smith (1989; Quintette and Bullmoose). Samples from the Northeast deposits are fresh, Intermontane samples are weathered, Comox samples include both fresh and weathered, and Nanaimo and Suquash samples are entirely from weathered outcrop and abandoned mine sites. Results of the analyses on Hat Creek (Goodarzi and Van der Flier-Keller, 1988), Tulameen (Goodarzi and Van der Flier-Keller, 1989), and Insular Belt (Van der Flier-Keller and Goodarzi, 1991) coals have previously been reported. REE were determined using INAA (Instrumental Neutron Activation Analysis) on coal ash, and reported back to the whole coal. Precision of the analyses based on duplicate samples is 0-5% for Nd, Sm, Eu, Yb, and Lu, 5-10% for La and Ce, and 10-15% for Tb.

RESULTS AND DISCUSSION

Mean REE abundances for samples from the seven deposits are given in Table 2. The Quintette and Suquash coals are, on average, most enriched in the REE. Suquash has the highest mean HREE values, close to the level in average north American shale (ANAS). Quintette shows highest mean LREE, while the concentrations of the HREE in the Quintette deposit are more similar to those in the other deposits. Quintette also exhibits a large negative Eu anomaly. Nanaimo and Comox are consistently least enriched in all REEs.

CHONDRITE-NORMALISED PATTERNS

Chondrite-normalised patterns are shown in Figure 1. Chondrite values are from Wakita et al. (1971). All of the deposits show enrichment of the LREE compared to the HREE. Negative Eu anomalies are present in all deposits with the exception of Comox and Nanaimo.

SHALE-NORMALISED PATTERNS

Shale-normalised patterns for the seven deposits are shown in Figure 2. Average North American shale (ANAS) values are from Haskin et al. (1968). In terms of absolute abundances, the coals are considerably depleted compared to ANAS. This is probably due to dilution by the organic matter content of the coals; however, the levels of HREE in the Suquash coal are close to those in

Table 1: Geological characteristics of the coal deposits examined.

Tulameen, B.C.	Intermontane	Eocene Allenby Formation	hvbA-B	Weathered
Hat Creek, B.C.	Intermontane	Eocene Hat Creek Coal Formation	lig-subbBC	Weathered
Suquash, B.C.	Insular	Upper Cretaceous Nanaimo Group	hvbC	Weathered
Comox, B.C.	Insular	Upper Cretaceous Nanaimo Group	hvbA	Mixed
Nanaimo, B.C.	Insular	Upper Cretaceous Nanaimo Group	hvbB	Weathered
Quintette, B.C.	NE Rocky Mt	Lower Cretaceous Gates Formation	mvb	Fresh
Bullmoose, B.C.	NE Rocky Mt	Lower Cretaceous Gates Formation	mvb	Fresh

Table 2: Mean REE abundances in western Canadian coals
(all values in ppm)

	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu
Tulameen	11.0	22.4	10.5	2.3	0.39	0.33	1.1	0.18
Hat Creek	8.4	20.5	8.3	1.9	0.40	-	1.1	0.20
Bullmoose	10.7	21.3	10.8	1.6	0.36	0.26	0.9	0.17
Quintette	17.5	32.3	12.8	2.4	0.39	0.36	1.3	0.25
Nanaimo	4.2	8.7	4.4	0.9	0.24	0.13	0.6	0.11
Comox	5.2	10.3	4.9	1.1	0.35	0.18	0.8	0.14
Suquash	9.5	22.6	10.5	2.4	0.69	0.60	2.7	0.47
ANAS	32.0	73.0	33.0	5.7	1.24	0.85	3.1	0.48

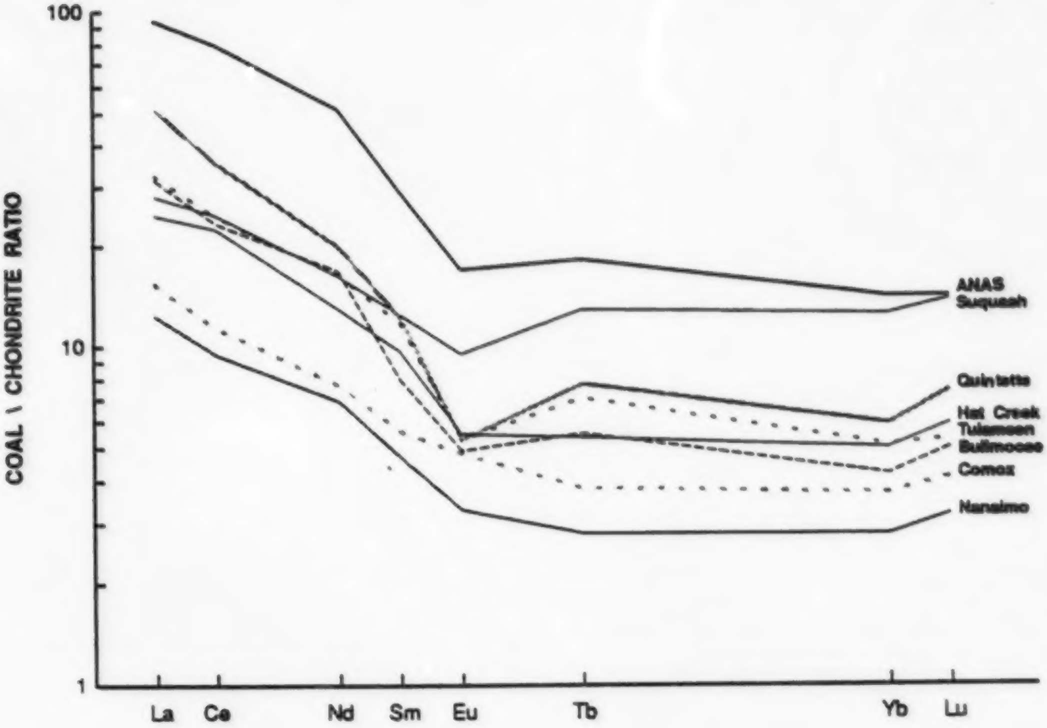

Figure 1: Chondrite-normalised REE patterns for western Canadian coals.

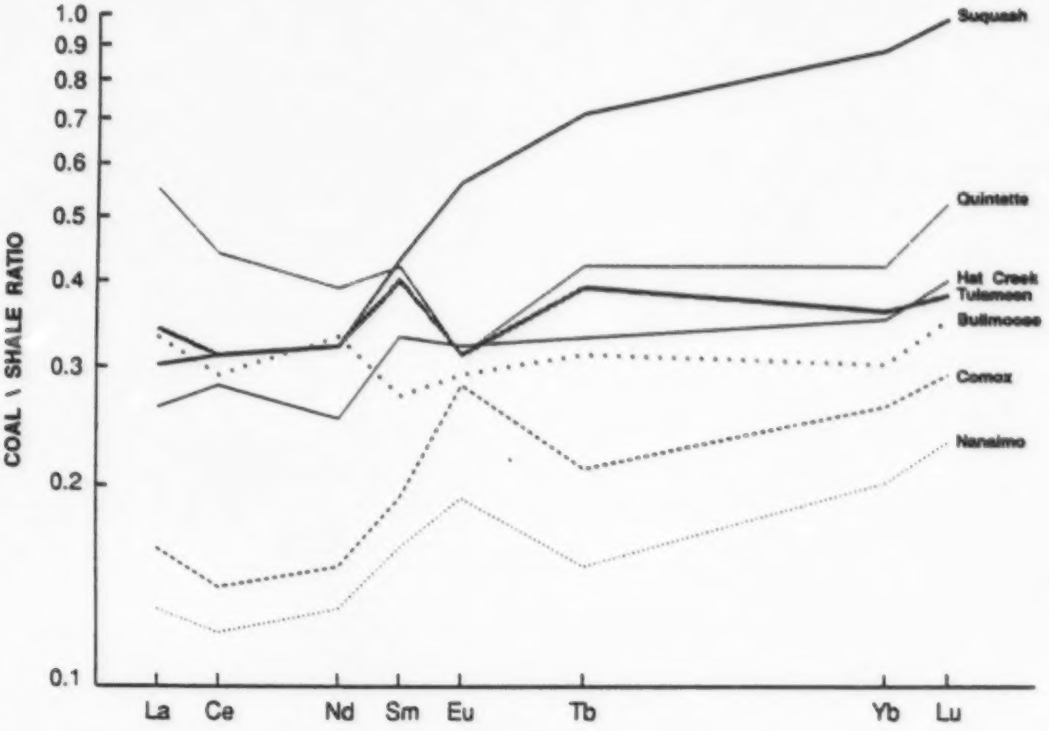

Figure 2: Shale-normalised REE patterns for western Canadian Coals.

ANAS. The shale-normalised patterns for the seven coal deposits are generally relatively flat, indicating little differentiation with respect to shale. There is a slight enrichment of the HREE compared to LREE for the Insular and Intermontane coals, while the Rocky Mountain coals exhibit negative Eu and Sm anomalies in the Quintette and Bullmoose deposits, respectively. The varying degrees of similarity of the coals with the ANAS may reflect the characteristics of the source area and the degree of homogenisation or maturity of the REE-bearing detrital components in each deposit relative to the source. In situations where a) the source areas to the coal contain representative crustal lithologies, and b) the derived REE-bearing phases are evenly represented in the coal, REE signatures comparable to the ANAS would be expected. Where a) the source area is perhaps smaller and the lithologies less representative, and/or b) the source REE-bearing phases are not evenly represented in the coal, some divergence from the ANAS signature is likely to exist. In the Cordilleran coals examined, the Rocky Mountain coals show most mature source signatures, while the Insular and Intermontane coals appear to retain individual characteristics of local sources.

Variations relative to ANAS may also be related to diagenetic effects. Post-depositional mobilisation of the REEs from a particular detrital mineral phase may be followed by selective capture of only a particular REE in, for example, an epigenetic mineral phase such as calcite.

MODE OF OCCURRENCE

REE have been reported to occur in a wide range of associations in coal, from inorganic (Eskenazy 1987a and b; Finkelman, 1980; Goodarzi and Van der Flier-Keller 1989, 1988; Lyons et al., 1989; and Palmer and Filby, 1984) to both organic and inorganic (Filby et al., 1977; and Gluskoter et al., 1977). These conclusions are based on a variety of techniques, including float-sink, regression analysis, SEM-EDX, and leaching experiments. Mineral phases with which the REE are suggested to occur include clay minerals (Bethell, 1962), RE-bearing phosphate minerals (Finkelman, 1980), and RE-silicates and/or apatite (Brown and Swaine, 1964; Swaine, 1964). Pearson Regression analysis and evaluation of shale-normalised data are used in this study to examine the mode of occurrence of the REE. High positive correlation coefficients with major and trace elements associated with mineral phases indicate that the REE are largely inorganically bound in all of the deposits. Highest coefficients are with Al, Th, Ti, and Ca, suggesting that REE are associated with mineral phases in which these elements are dominant, i.e., clay minerals, heavy accessory minerals, and calcite (Table 3). Association with the clay minerals is likely through adsorption on surfaces (Roaldset and Rosenqvist, 1971a; Fleet, 1984). Alternatively, the high correlation coefficients with Al may represent an association with the clay-size fraction of the sediment, due to a physical sedimentologic effect as opposed to a chemical effect (e.g. Palmer and Filby, 1984). Where the REE are hosted in accessory minerals, the REE are probably substituting for large cations such as Y, Th, U, Zr, and P, in minerals such as rutile (Ti), zircon (Zr), monazite (Th), xenotime (Y), and chromite (Cr). Occurrence in calcite (for example in the Tulameen coal) is likely through substitution for Ca and/or Sr. Lesser degrees of association with Fe-bearing phases (possibly sulphides, or detrital unweathered pyroxenes or hornblendes) may be important in, for example, the Nanaimo coals.

Table 3: Suggested modes of occurrence of REE from Pearson Correlation coefficients.

Tulameen	clay minerals
	detrital heavy minerals (monazite, rutile)
	calcite (Eu, Lu)
Comox	clay minerals
	heavy minerals (rutile, monazite, zircon, chromite)
Nanaimo	clay minerals
	heavy minerals (monazite, xenotime)
	Fe-bearing phases (sulphides, organic matter)
Suquash	heavy minerals (HREE)
	clay minerals (LREE)
Quintette	clay minerals
	heavy minerals
Bullmoose	heavy minerals

VERTICAL PROFILES WITHIN THE DEPOSITS

Vertical profiles are examined for the Tulameen (Intermontane Belt), Comox (Insular Belt), and Quintette (Northeast Rocky Mountain Belt) deposits.

Tulameen

Vertical distributions of the REE in the Blakeburn mine (Tulameen) are shown in Figure 3. REE concentrations do not show an overall increase or decrease with depth in the section. Rather, the sometimes marked variations in concentration are closely associated with vertical variations in ash contents of samples from the profile. The vertical variations of LREEs parallel most closely those for Th. Europium is most similar to Al, and the HREE more similar to Ti. Certain thin stratigraphic horizons have marked enrichments in the HREE compared with LREE. If ratios of Ce/Lu are taken to represent the ratio of LREE to HREE, values greater than 100 are characteristic of the Tulameen profile; for example, at 11m depth the Ce/Lu ratio is 470. Variations from this occur, such as at 7.6m depth where the ratio is 67. Such significant ratio differences indicating relative enrichments of the HREE, may reflect temporal variations in available source constituents, e.g., a volcanic event (supply of HREE-enriched detrital minerals). If the effects of such source variations are consistent along strike, as might be expected if they are related to volcanic events, they may represent a possibility for using REEs in coals for correlation.

Shale-normalised REE patterns for a coal and carbonaceous shale within each of the three cycles of the Tulameen sequence (as outlined in Goodarzi and Van der Flier-Keller, 1989) are shown in Figure 4. While the HREE in the coals and shales relative to ANAS from each cycle are similar, the LREE show a pattern, for both lithologies relative to ANAS, of progressively decreasing values with depth in the section. The patterns in the upper cycle (Cycle 3, samples 3-57 and 3-61) are relatively undifferentiated with respect to ANAS, and values are close to unity. In the lowest cycle (Cycle 1) in low-ash coal (sample 1-11), the pattern shows significant differentiation with respect to ANAS, and the ratios for LREE are low.

Comox

Vertical distributions of the REE in the Quinsam deposit (Comox) are shown in Figure 5. There is no net change in REE concentrations with depth in the section, rather concentrations vary with ash values, and in particular the Zr and Al content of the samples.

In the basal parting of the Number one (lower) seam, Ce to Yb are enriched relative to the La. In the parting stratigraphically above, La and Ce are enriched relative to the HREE. This may indicate a temporary source rock change, or some mobilisation of the HREE downward in the section.

Quintette

The vertical profile for the REE in the Quintette section exhibits a gradual down-section increase to the middle of the section and a subsequent sharp decrease towards the base. The pattern corresponds broadly with the vertical distribution of ash, and Al, Th, Ti and Th; however, the shape of the curve is different in detail. In particular low Al, Th, and Zr values occur in seam D4, where REE contents are highest for Eu and Tb.

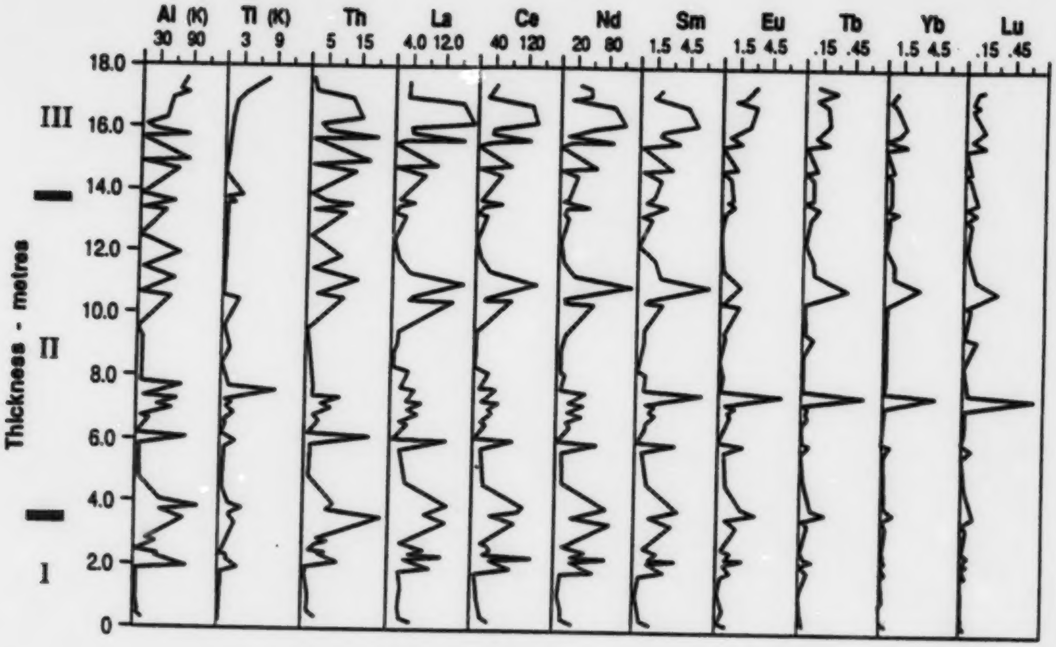

Figure 3: Vertical distributions of the REE in the Blakeburn mine, Tulameen coal deposit.

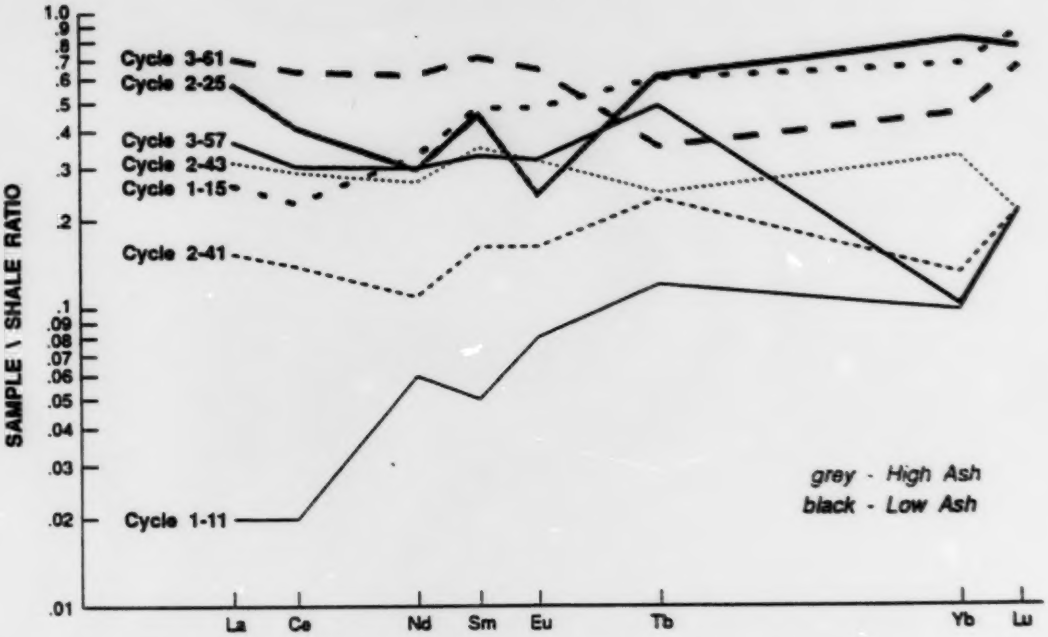

Figure 4: Shale-normalised REE patterns for coal and carbonaceous shale samples from Blakeburn mine, Tulameen coal deposit.

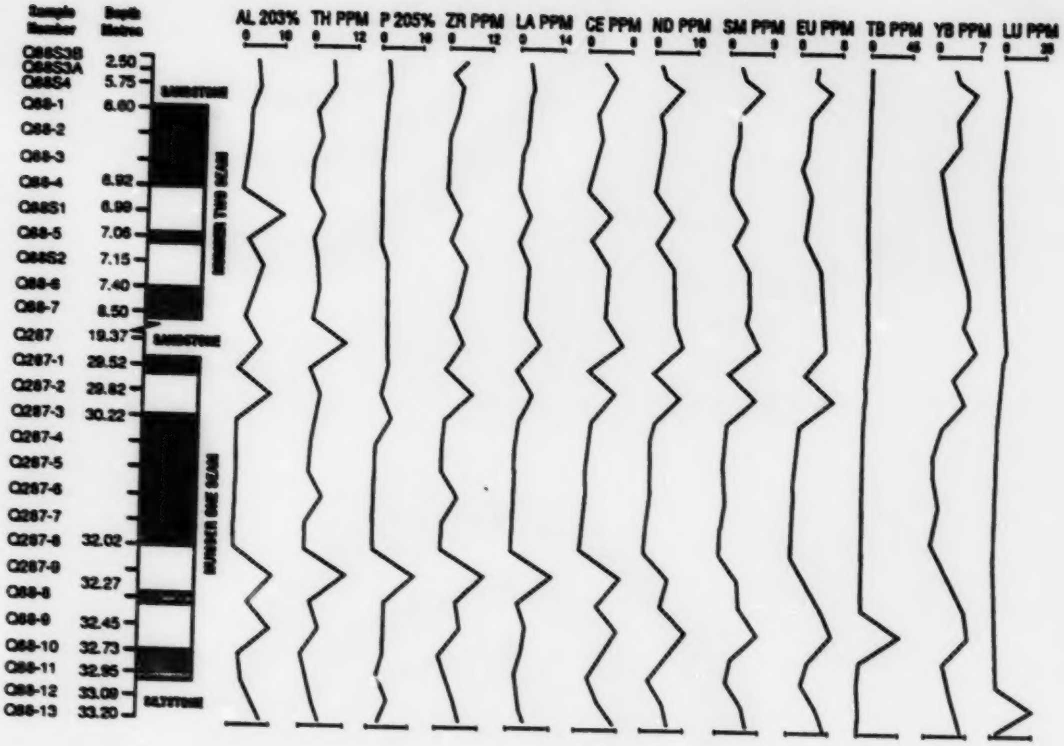

Figure 5: Vertical distributions of the REE in the Quinsam mine, Comox coal deposit.

CONTROLS ON REE CHARACTERISTICS OF COAL DEPOSITS

Goldschmidt and Peters (1933) suggested that some biological accumulation of REE may have occurred during the early stages of coal formation. Eskenazy (1987a) also discusses an original organic control on REE patterns in Bulgarian coals, on the basis of Eu anomalies. Swaine (1990) points out that although an original organic input or control on REE may be important, the REE may not necessarily remain organically bound during diagenesis. Lyons et al. (1989) state that basinal geochemical signatures are seen in REE data for a series of coal beds from the Eastern United States. The REEs in these coals are inorganically associated, suggesting that these patterns are probably associated with mineralogical differences between basins. Basinal mineralogical differences could result from a variety of processes ranging from original detrital input, i.e., source variability, to variations in basinal geochemical conditions which would affect the post-depositional mineralisation patterns. Dawson and Siefert (1986) suggest that, if inorganically associated, REEs would be expected to increase in concentration with increasing coal rank.

For the Cordilleran coals examined, rank and age are not directly related to REE characteristics. Rather the REE variations appear to be related to the abundance of specific mineral forms in the ash. Coal mineralogy is, in turn, related to source lithologies (for detrital minerals), and the varying geochemical conditions during coal formation (for diagenetic minerals). Source rocks are suggested to be fundamentally important since they control the initial detrital input into the system, both in terms of the nature of the mineral phases and the relative quantities of each mineral. The majority of the heavy detrital minerals and much of the clay mineral fraction, with which the REE are suggested to be associated, are likely to have been introduced during deposition. Iron-bearing minerals and calcite are in contrast characteristically diagenetic in many of the deposits. Clay minerals may be modified during coalification, resulting in potential mobilisation of the REE if surficially bound (Fleet, 1984). Geochemical conditions in the coal will determine the extent of this remobilisation.

There appear to be no major differences in REE characteristics between weathered and unweathered samples. For example, although the Comox and Nanaimo coals represent mixed weathered and unweathered, and weathered samples, respectively, they exhibit very similar mean shale-normalised REE patterns. Martin et al. (1976) suggest that since only a very few percent of REE entering the ocean are dissolved, weathering and erosion must result in only very minor amounts of REE going into solution.

CONCLUSIONS

REE concentrations in seven western Canadian coals are variable. Mean LREE and HREE values are highest in the Quintette (32.3ppm Ce) and Suquash (0.47ppm Lu) coals, respectively, while values for all the REE are lowest in the Nanaimo (8.7ppm Ce, 0.11ppm Lu) and Comox coals. REE concentrations are relatively undifferentiated with respect to shale (ANAS), except in the Insular Belt coals, which are HREE enriched. REEs are associated with the inorganic constituents in these coals, in particular clay minerals, heavy minerals and calcite. Vertical distributions correspond to variability in ash content. Certain horizons, where anomalous REE characteristics occur, may potentially be useful for correlation purposes. REE patterns do not reflect age or rank of the deposits, but are thought to be controlled by source lithologies and geochemical conditions during coalification.

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NOTES

INDEX TO AUTHORS WITH AFFILIATION AND TITLE OF ABSTRACT OR PAPER

AUTHOR	PAGE	AFFILIATION/TITLE
H. J. Abercrombie	243	Institute of Sedimentary and Petroleum Geology, Calgary *Coalbed Methane Potential of selected Kootenay Coals in relation to petrographic and mineralogic characteristics*
E.J. Allen	147	LAS Energy Consultants, Calgary *Coalbed methane potential in northeast British Columbia*
W.B. Ayers	3	Taurus Exploration Inc., Alabama *Coalbed methane occurrence and producibility, Fruitland Formation, Navajo Lake area San Juan Basin New Mexico*
K.M. Baak	21	Roke Oil Enterprises Ltd., Calgary *Quad neutron logs and coalbed methane*
A.P. Beaton	245	Department of Geology, University of Western Ontario *Characterization of coals from the Whitehorse Trough Yukon Territory*
A.P. Beaton	315	Department of Geology, University of Western Ontario *Geochemistry of coals and associated sedimentary rocks from Elk Valley Coalfield, British Colubia*
R.A. Benkis	265	Monenco Engineering, Calgary *An overview of some selected coal resources of the world*
J. Briker	175	Alberta Research Council, Devon *Air pollution control by application of AGLOFLOAT process for cleaning high sulphur bituminous coals*
M.R. Bustin	87	Geology Department, University of British Columbia *Coalbed methane characteristics of Gates Formation lithotypes, northeastern British Columbia*
K. Burchard	243	Institute of Sedimentary and Petroleum Geology, Calgary *Coalbed Methane Potential of selected Kootenay coals in relation to petrographic and mineralogic characteristics*
J.H. Calder	365	Nova Scotia Department of Natural Resources *Controls on formation of upper Carboniferous coals in the intermontane Stellarton and Cumberland Basins of Atlantic Canada*
J.H. Calder	313	Nova Scotia Department of Natural Resources *Geochemistry of carboniferous coals from Sprinfield Coalfield, Nova Scotia*
D.A. Cameron	315	Insitute of Sedimentary and Petroleum Geology, Calgary *Geochemistry of coals and associated sedimentary rocks from the Elk Valley Coalfield, British Columbia, Canada*

D.A. Cameron	245	Institute of Sedimentary and Petroleum Geology, Calgary *Characterization of coals from the Whitehorse Trough Yukon Territory*
J.C. Campbell	23	Cape Breton Development Corporation, Nova Scotia *Utilization alternatives for coalbed methane from the Sydney Coalfield in Nova Scotia*
G. Capobianco	291	Coal Association of Canada, Calgary *Coal and the Environment*
J.D. Carlson	39	Sproule Associates Limited, Cagary *Economics of Coalbed methane projects in the Western Canada Basin*
C. G.Cathyl-Bickford	361	Westwater Mining Ltd., Calgary *Geology of the Quinsam Coalfield*
C. G.Cathyl-Bickford	293	Westwater Mining Ltd., Calgary *Geology, mineability and resource appraisal of the Douglas Seam in the Nanaimo Coalfield*
R. Cech	39	Sproule Associates Limited, Calgary *Economics of Coalbed methane projects in the Western Canada Basin*
D.K. Chao	401	Alberta Research Council, Edmonton *Coal Compilation Progect Geoscience Information System (GSIS) supported coal resource mapping in Alberta*
J.T. Clow	57	Western Atlas Canada Ltd. Core Laboratory Division, Calgary *Coalbed methane research southeast British Columbia*
J. Cunningham	311	B.C. Geological Survey, Victoria *Peace River Digital Mappping Program*
F.M. Dawson	57	Institute of Sedimentary and Petroleum Geology, Calgary *Coalbed methane research southeast British Columbia*
J. Ellard	73	Taurus Exploration Inc., Alabama *Coalbed methane production from the Pottsville Formation at Cedar Cove Field, Black Warrior Basin, Alabama U.S.A.*
D. Fietz	401	Elad Enterprizes , Calgary *Coal Compilation Progect Geoscience Information System (GSIS) supported coal resource mapping in Alberta*
P. Gilmar	187	Westar Mining, Sparwood B.C. *Westar Mining's Balmer Operations Coal Quality Control*
F. Goodarzi	245	Institute of Sedimentary and Petroleum Geology, Calgary *Characterization of coals from the Whitehorse Trough Yukon Territory*

F. Goodarzi	313	Institute of Sedimentary and Petroleum Geology, Calgary *Geochemistry of Carboniferous coals from Springfield Coalfield, Nova Scotia*
F. Goodarzi	317	Institute of Sedimentary and Petroleum Geology, Calgary *Geochemistry of Bowron River coal deposit British Columbia*
F. Goodarzi	319	Institute of Sedimentary and Petroleum Geology, Calgary *Geochemistry of Boron in Australian and Canadian Coals*
F. Goodarzi	315	Institute of Sedimentary and Petroleum Geology, Calgary *Geochemistry of coals and associated sedimentary rocks from the Elk Valley Coalfield British Columbia, Canada*
D.L. Granatstein	23	Nova Scotia Power Corporation *Utilization alternatives for coalbed methane from the Sydney Coalfield in Nova Scotia*
A.C. Grant	333	Atlantic Geoscience Centre, Dartmouth, Nova Scotia *Seismic character of coal measures, Gulf of St. Lawrence Region*
D.A. Grieve	35	B.C. Geological Survey Branch, Victoria *Phosphorus in British Columbia coking coals*
D.A. Grieve	315	B.C. Geological Survey Branch, Victoria *Geochemistry of coals and associated sedimentary rocks from the Elk Valley Coalfield British Columbia, Canada*
D.A. Grieve	355	B.C. Geological Survey Branch, Victoria *Relationships between coal quality parameters in British Columbia coals*
J. Henderson	213	Geo-Pysi-Con, Calgary *Coal Planning and Surface Geophysics at Coal Mountain*
G. L. Hoffman	293	Westwater Mining Ltd., Calgary *Geology, mineability and resource appraisal of the Douglas Seam in the Nanaimo Coalfield*
M.E. Holuszko	211	B.C. Geological Survey Branch, Victoria *Washability of British Columbia coals*
M.E. Holuszko	187	B.C. Geological Survey Branch, Victoria *Washability of Peace River and East Kootenay coals*
J.D. Hughes	357	Institute of Sedimentary and Petroleum Geology, Calgary *G.I.S. and three-dimentional CAD applied to computer-modelling of coalfields*
B. Ignasiak	175	Alberta Research Council, Devon *Air pollution control by application of AGLOFLOAT process for cleaning high sulphur bituminous coals*

P. Jahans	359	University of Alberta, Edmonton *Pine Valley Mapping and Compilation Project*
D.G.S. Johnson	147	LAS Energy Consultants, Calgary *Coalbed methane potential in northeast British Columbia*
D.G.S. Johnson	85	LAS Energy Consultants, Calgary *Coalbed methane in southeast British Columbia and structure of the Crowsnest Coalfield (Fernie Basin)*
J.P. Jurrius	141	Carbon Energy International *Optimization of geotechnical and economic factors influencing coalbed methane exploration projects*
W.R. Kaiser	3	Taurus Exploration Inc., Alabama *Coalbed methane occurrence and producibility, Fruitland Formation, Navajo Lake area San Juan Basin New Mexico*
W.D. Kalkreuth	243	Institute of Sedimentary and Petroleum Geology, Calgary *Coalbed Methane Potential of selected Kootenay coals in relation to petrographic and mineralogic characteristics*
W.D. Kalkreuth	399	Institute of Sedimentary and Petroleum Geology, Calgary *Petrographic examination of coal lithotype samples from the lower Cretaceous Gates FM: A comparison of automated image analysis vs manual microspy*
C. Kenyon	361	B.C. Geological Survey Branch, Victoria *Geology of the Quinsam Coalfield*
W.E. Kilby	363	B.C. Geological Survey Branch, Victoria *Digital mapping-tools*
J. Kramer	175	Alberta Research Council, Devon *Air pollution control by application of AGLOFLOAT process for cleaning high sulphur bituminous coals*
M. Labonte	315	Institute of Sedimentary and Petroleum Geology, Calgary *Geochemistry of coals and associated sedimentary rocks from the Elk Valley Coalfield British Columbia, Canada*
T.C. Lam	231	Monenco Engineering, Calgary *Using geophysical logs to predict geotechnical parameters in surface coal mines*
M.N. Lamberson	87	University of British Columbia *Coalbed methane characteristics of Gates Formation lithotypes, northeastern British Columbia*
W. Langenberg	401	Alberta Research Council, Edmonton *Coal Compilation Progect Geoscience Information System (GSIS) supported coal resource mapping in Alberta*

W. Langenberg	103	Alberta Research Council, Edmonton *Geology and Coalbed methane potential of the Foothills in the Cadomin area, Alberta*
L. Lottman-Craigg	117	GeoMet Inc., Ashburn, VA. *A method of fracture analysis to optimize coalbed methane production*
A.R. MacLean	23	Cape Breton Development Corporation, Nova Scotia *Utilization alternatives for coalbed methane from the Sydney Coalfield in Nova Scotia*
R.K. MacLeod	39	Sproule Associates Limited, Calgary *Economics of Coalbed methane projects in the Western Canada Basin*
P. Malone	117	GeoMet Inc, Ashburn, VA. *A method of fracture analysis to optimize coalbed methane production*
T.A. Martel	365	Department of Earth Sciences, Oxford University, Oxford *Controls on formation of upper Carboniferous coals in the intermontane Stellarton and Cumberland Basins of Atlantic Canada*
D.L. Marchioni	399	Institute of Sedimentary and Petroleum Geology, Calgary *Petrographic examination of coal lithotype samples from the Lower Cretaceous Gates Formation: a comparison of automated image analysis versus manual microscopy.*
A. Matheson	317	B.C. Geological Survey Branch, Victoria *Geochemistry of Bowron River coal deposit British Columbia*
M. Mavor	119	Resource Enterprises Inc., Salt Lake City, Utah *Evaluation of coalbed natural gas open hole cavity completion productivity*
R.D. Naylor	365	Nova Scotia Department of Natural resources *Controls on formation of upper Carboniferous coals in the intermontane Stellarton and Cumberland Basins of Atlantic Canada*
D. Nikols	411	Alberta Research Council, Edmonton *Coal geoscience program; Alberta Geological Survey*
S.P. Pappajohn	141	Carbon Energy International *Optimization of geotechnical and economic factors influencing coalbed methane exploration projects*
W. Pawlak	175	Alberta Research Council, Devon *Air pollution control by application of AGLOFLOAT process for cleaning high sulphur bituminous coals*

A. Peach	213	Byron Creek Collieries, Sparwood B.C. *Coal Planning andSurface Geophysics at Coal Mountain*
K.C. Pratt	399	Institute of Sedimentary and Petroleum Geology, Calgary *Petrographic examination of coal lithotype samples from the Lower Cretaceous Gates Formation: a comparison of automated image analysis versus manual microscopy.*
R.J.H. Richardson	401	Alberta Research Council, Edmonton *Coal Compilation Progect Geoscience Information System (GSIS) supported coal resource mapping in Alberta*
R.J.H. Richardson	411	Alberta Research Council, Edmonton *Coal geoscience program; Alberta Geological Survey*
R.J.H. Richardson	143	Alberta Research Council, Edmonton *Coalbed methane research at the Alberta Geological Survey*
R. Roark	73	Taurus Exploration Inc., Alabama *Coalbed methane production from the Pottsville Formation at Cedar Cove Field Black Warrior Basin, Alabama U.S.A.*
B.A. Rottenfusser	143	Alberta Research Council, Edmonton *Coal bed methane reasearch at the Alberta Geological Survey*
J. Rowling	145	B.C. Petroleum Geology Branch, Victoria *Coalbed methane resources in British Columbia*
B.D. Ryan	413	B.C. Geological Survey, Victoria *Coalbed Methane resource potential and coal washability at the Telkwa coal deposit central British Columbia*
B.D. Ryan	415	B.C. Geological Survey, Victoria *Potential Coke Strength after Reaction of British Columbia Coals*
R.J. Ryan	365	Nova Scotia Department of Natural Resources *Controls on formation of upper Carboniferous coals in the intermontane Stellarton and Cumberland Basins of Atlantic Canada*
M. Sadre	317	Department of Geology, University of Western Ontario *Geochemistry of Bowron River coal deposit British Columbia*
L.A. Smith	85	LAS Energy Consultants, Calgary *Coalbed methane in southeast British Columbia and structure of the Crowsnest Coalfield (Fernie Basin)*
L.A. Smith	147	LAS Energy Consultants, Calgary *Coalbed methane potential in northeast British Columbia*
B. Sprecher	311	B.C. Geological Survey Branch, Victoria *Peace River digital mapping program*

M. Steller	399	Institute of Sedimentary and Petroleum Geology, Calgary *Petrographic examination of coal lithotype samples from the Lower Cretaceous Gates Formation: a comparison of automated image analysis versus manual microscopy.*
H. Stellmach	229	Line Creek Resources, Calgary *Utilization of Western Canadian Metallurical Coals*
D.J. Swaine	319	CSRIO Division of Coal and Technology, Australia *Geochemistry of Boron in Australian and Canadian Coal*
K. Szymocha	175	Alberta Research Council, Devon *Air pollution control by application of AGLOFLOAT process for cleaning high sulphur bituminous coals*
J.C. UnKauf	147	LAS Energy Consultants, Calgary *Coalbed methane potential in northeast British Columbia*
E. Van der Flier-Keller	417	Department of Geology, University of Victoria *Rare Earth Element patterns in seven western Canadian coals*
N.H. Wade	231	Monenco Engineering, Calgary *Using geophysical logs to predict geotechnical parameters in surface mines*
M. Whiticar	149	Department of Geology, University of Victoria *Stable Isotope geochemistry of coals humic Kerogens and related natural Gases*
R. Wilson	293	Westwater Mining Ltd., Calgary *Geology, mineability and resource appraisal of the Douglas Seam in the Nanaimo Coalfield*

APPENDIX

NOTES

UTILIZATION OF WESTERN CANADIAN METALLURGICAL COAL

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OVERVIEW

The paper briefly outlines international markets for metallurgical coal with specific reference to the role of western Canadian coal. Coke and iron making processes are reviewed to highlight customer requirements for various coal quality characteristics. The technical attributes of western Canadian coals are discussed in relation to other internationally traded coals. The impact of new technical developments in coke and iron making on western Canadian coal exports are also discussed.

MARKET BACKGROUND

In 1990 the Canadian coal industry produced 68.4 million tonnes of coal. Of this total, 31 million tonnes were exported. Exports consisted of 4.1 million tonnes of thermal coal (primarily for power generation) and 26.9 million tonnes of metallurgical coal (Figure 1). Metallurgical (or coking) coal is used in the production of coke which in turn is used primarily for the production of blast furnace iron and steel.

Except for relatively small trial quantities, steel mills in Ontario have traditionally imported their coking coal requirement from the nearby U.S.A. coal fields. Therefore, Utilization of Western Canadian Metallurgical Coal, in essence refers to utilization of exported coal. Imports from the U.S.A. to Ontario in 1990 were 4.5 million tonnes of coking and 9.7 million tonnes of thermal coal.

The western Canadian coal export industry developed over a period of about 15 years, from the late 1960's to the early 1980's. Mine developments, infrastructure, railways and ports were put in place in response to metallurgical coal demand from Japan. Changing demand since that time, however, has forced the industry to diversify its markets in order to survive. Figure 2 shows Canadian metallurgical coal exports by year and destination. The Japanese market has always been and still is by far the largest representing about 62% of total sales in 1990. The figure illustrates the changing trade patterns over the last 15 years. Greater emphasis is now being given the coal movements to Latin America, Europe and the U.S.A. as well as Korea and Taiwan.

The increased customer diversification has occurred largely as a result of recognition by other steel mills of the technical benefits which western Canadian coal provides in the production of blast furnace coke. However, strong market competition in the far east also contributed to this diversification.

The future utilization of western Canadian metallurgical coals is integrally linked to the international steel demand. Figure 3 shows a projection of the Regional Steel Output to 2005. Growth is expected to be less that 1% per year. Making allowance for anticipated changes in steel making technologies, the steel demand translates into the regional Coking Coal Imports shown on Figure 4. As can be seen, the Far East will continue to be the dominant market area. Taking this one step further, Figure 5 gives a projection of the world coking coal export picture. Only limited demand growth can be anticipated, this also being in the order of 1% per year. Australia, U.S.A. and Canada are the main supply areas. Most of the growth however, will be taken up by Australia, the low cost producer. Canada will have to work hard to retain its position and make

FIGURE 1

1990 CANADIAN COAL SUPPLY/DEMAND
(MILLION TONNES)

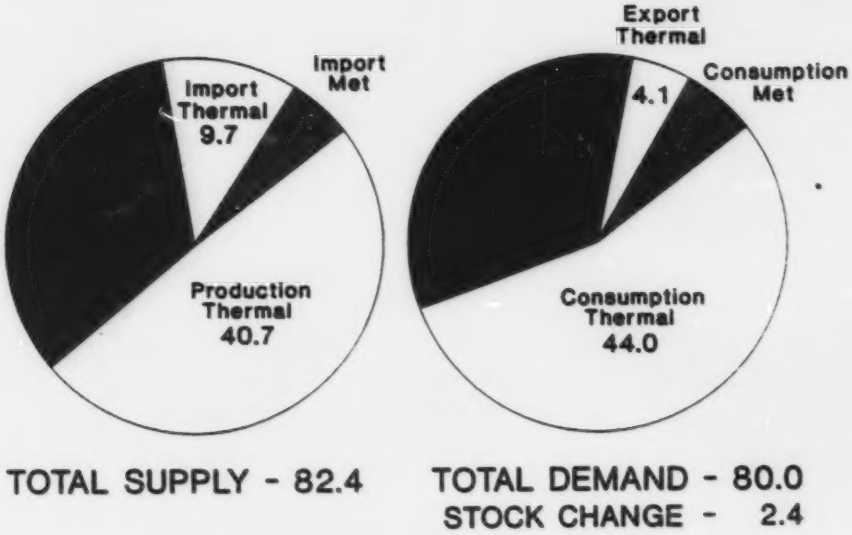


FIGURE 2

CANADIAN METALLURGICAL COAL EXPORTS

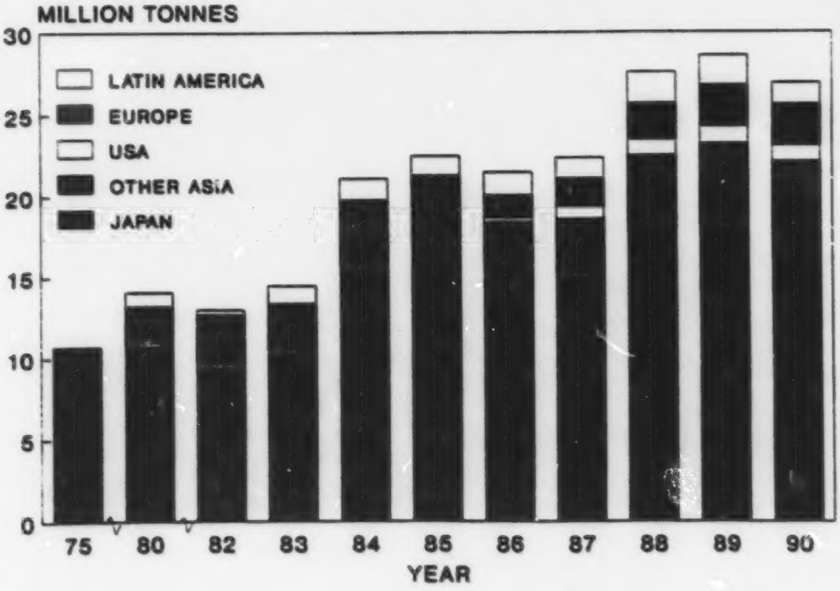
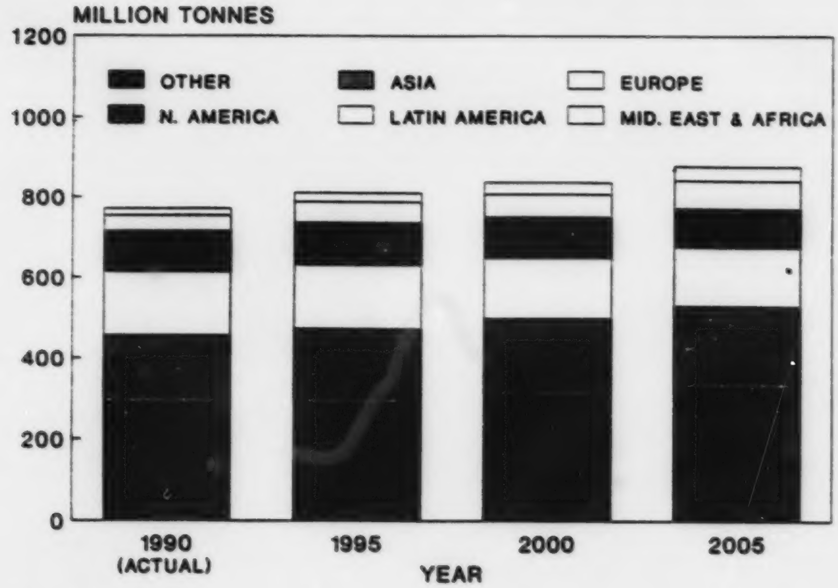


FIGURE 3

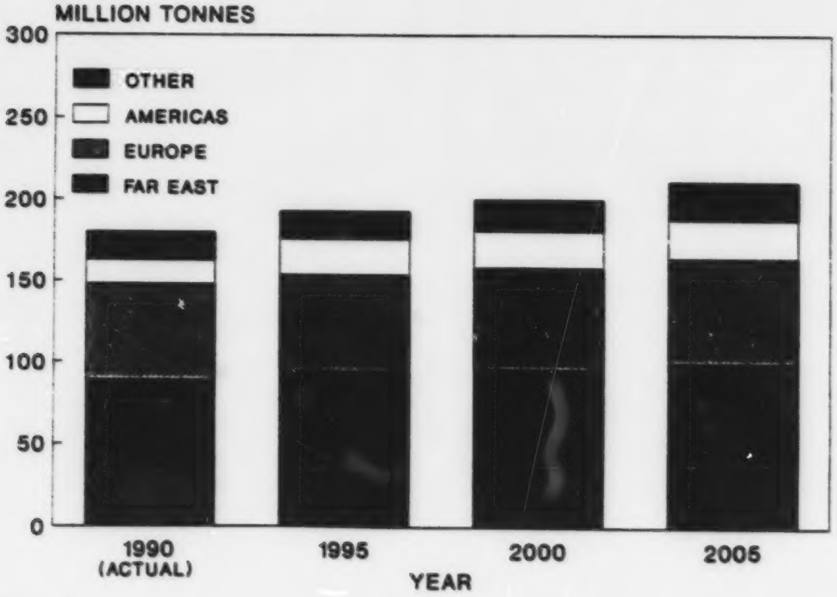
REGIONAL STEEL OUTPUT



SOURCE: SCI

FIGURE 4

REGIONAL COKING COAL IMPORTS



SOURCE: SCI

small gains. The trend toward greater use of cheaper weak and non-coking coals (described later in this paper) will further increase the competitive pressure.

COAL QUALITY REQUIREMENTS FOR COKE MAKING

As this is a very broad subject area, the coverage in this paper must, by necessity, be very general. Few individual coals meet all the requirements to produce high quality coke. Fortunately coals can be blended to so that a deficiency in one quality parameter can be compensated for by a surplus of that parameter in another coal. Coke makers may use blends with as few as two coals or as many as 20.

Western Canadian coking coals range in rank from high volatile bituminous to low volatile bituminous. However, most are typically in the medium volatile category.

Typical quality ranges of western Canadian metallurgical coals are:

Total Moisture (ar)		7 to 8%
Ash (db)		6 to 10%
Volatile Matter (db)		17 to 32%
Sulphur		0.25 to 0.6%
Alkalies		0.04 to 0.12%
Mean Max Reflectance		0.9 to 1.65%
FSI		5.5 to 8
Fluidity, ddpm		5 to 1000
HGI		65 to 95
Size, minus 50 mm		100%
Max. Oven wall pressure,	kPa	2 to 16
	psi	0.3 to 2.3

The quality attributes of western Canadian coking coals are (under gross generalization) quite different from European and U.S. Appalachian coals of similar rank. The western Canadian coals tend to have:

- lower reactives (vitrinite), higher inerts (fusinite & semi-fusinite)
- lower thermal rheological properties
- higher inherent ash
- lower sulphur
- lower alkalies
- higher phosphorus
- higher coke strength after reaction, lower coke reactivity
- lower coking pressure
- more friability

While a number of the Canadian coals make excellent coke when carbonized alone, the coals perform best when carbonized in blends with lower inerts and higher fluid properties.

Australian coals have many characteristics similar to western Canadian coals. As a result the Canadian and Australian coals, compete with each other. On the other hand, both the Australian and Canadian coals tend to complement coals from the U.S.A. and Europe. Therefore, the value of a specific Canadian coal quality attribute is dependent upon where the coal is used and what other coals have ready access to the same market.

In order to review the quality requirements and attributes of metallurgical coal it will be helpful to describe:

1) How coke is produced and what some of the constraints are in the production process.

2) How the coke is consumed, and what its function and characteristics should be.

COKE MAKING PROCESS

Present day metallurgical coke is produced in by-product coke batteries made up of 30 to 100 (or more) slot-type ovens. Ovens are constructed of high temperature refractory brick within a steel support frame. Each oven chamber is typically 460 mm wide, 15 m long and 3 to 7 m high. Beside each oven chamber is a heating chamber consisting of a series of hair-pin heating/combustion flues. The battery line-up therefore consists of alternating coking and heating chambers so that each coking chamber is between two heating chambers (Figure 6).

In the process, coal is crushed to 80% minus 3 mm and is charged into the ovens via three or more charge holes on top of each oven. The coal in the coking chamber is heated by heat transfer through the refractory side walls, from the heating chambers. As the coal heats up, moisture and volatile hydrocarbons are driven off and are piped to the by-product plant for processing. When the coal nearest to the heating wall on each side of the oven reaches 375 to 400°C the coal begins to soften forming a vertical viscous or plastic layer (Figure 7). As more heat is added to the coal, this plastic layer moves from the sidewalls to the centre of the oven. Thus on the inside of the layer, the coal is relatively unchanged whereas on the outside of the layer the coal has been transformed to coke. When the plastic layers meet in the centre, and the temperature has risen to 1050 to 1100°C, carbonization is complete. After this, doors at each end of the oven are opened and the coke charge is pushed out as a single cake, using a large mechanical ram. The doors are then closed and the ovens are recharged. The hot coke is cooled down either using a water quench or an enclosed circulating inert gas, dry quench system. One oven cycle will take from 16 to 26 hours depending on such things as charge moisture, bulk density, and heating rate.

THE BLAST FURNACE IRON MAKING PROCESS

The blast furnace is the heart of the iron making process; a schematic is shown in Figure 8. The modern blast furnace is a massive refractory lined structure with a total height of about 100 m and an inner volume of up to 4,000 to 5,000 cu. meters producing 8,000 to 12,000 tonnes per day of hot metal. Coke and iron ore are charged in alternating layers to the furnace top. Preheated air or oxygen enriched air is blown via tuyeres into the bottom of the furnace. The hot air reacts with the coke to produce carbon monoxide and nitrogen. The hot gas passes up the furnace, stripping oxygen from the iron ore, and exits the top of the furnace at about 200°C.

Liquid, iron and slag collect at the bottom of the furnace from where they are tapped off periodically.

THE ROLE OF COKE IN THE BLAST FURNACE

The quality of the coke charged to the blast furnace (and the quality of the coal which makes up the coke) determines the effectiveness of the blast furnace process. Coke has three basic functions in the blast furnace:

1. To act as fuel to provide the heat and temperature required to melt the iron and slag and to provide heat for endothermic reactions.

2. To produce and regenerate reducing gas for the reduction of the iron ore, according to the reactions:

$$2C + O_2 = 2CO$$

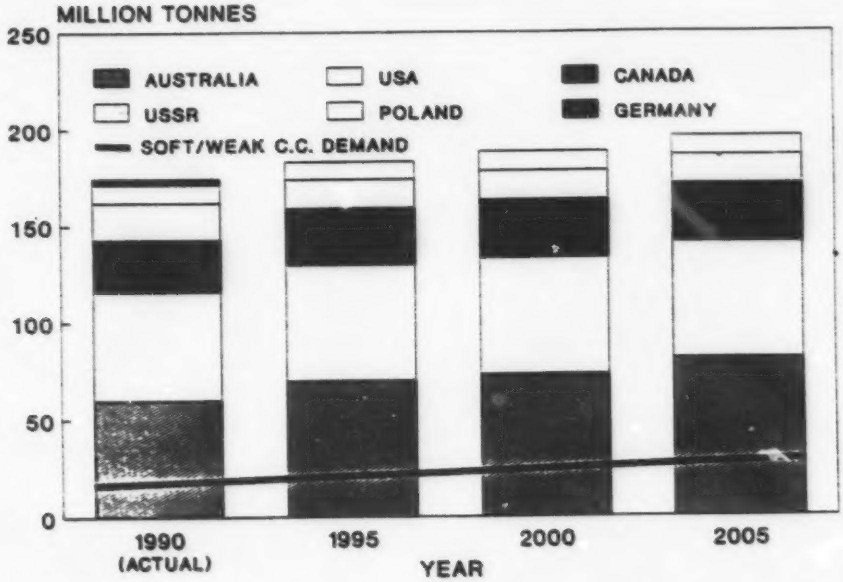
$$Fe_2O_3 + 3CO = 2Fe + 3CO_2$$

$$CO_2 + C = 2CO \text{ (above 1000°C)}$$

3. To provide a permeable bed through which liquid iron and slag and gas can easily pass in counter-current flow.

FIGURE 5

COKING COAL EXPORTS



SOURCE: SCI

FIGURE 6

TYPICAL COKE OVEN SECTION

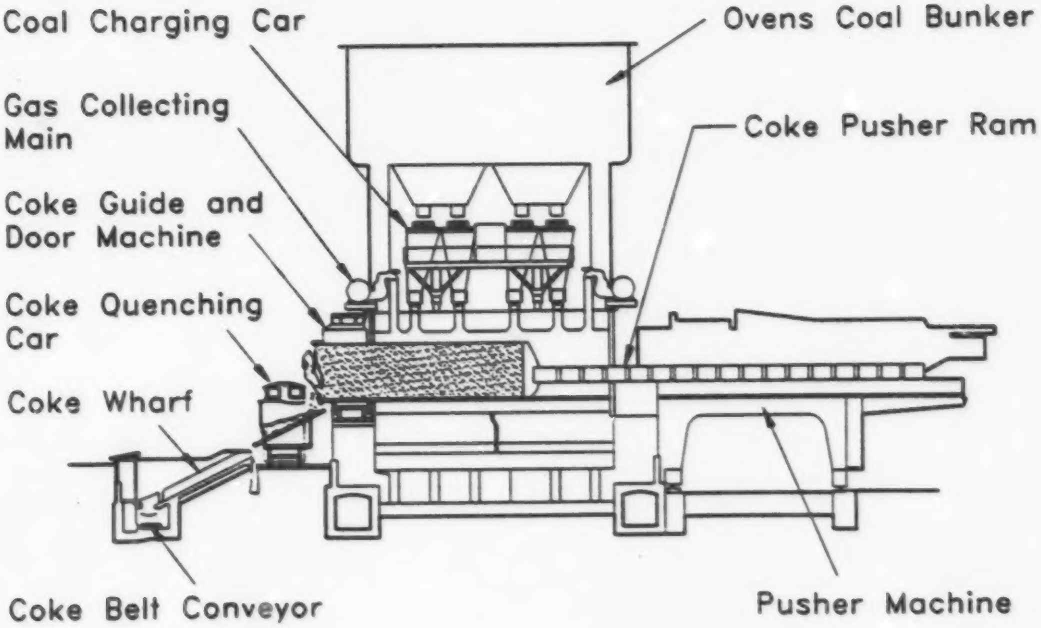

Coal Charging Car
Ovens Coal Bunker
Gas Collecting Main
Coke Pusher Ram
Coke Guide and Door Machine
Coke Quenching Car
Coke Wharf
Coke Belt Conveyor
Pusher Machine

FIGURE 7
SCHEMATIC CROSS-SECTION OF COKE OVEN

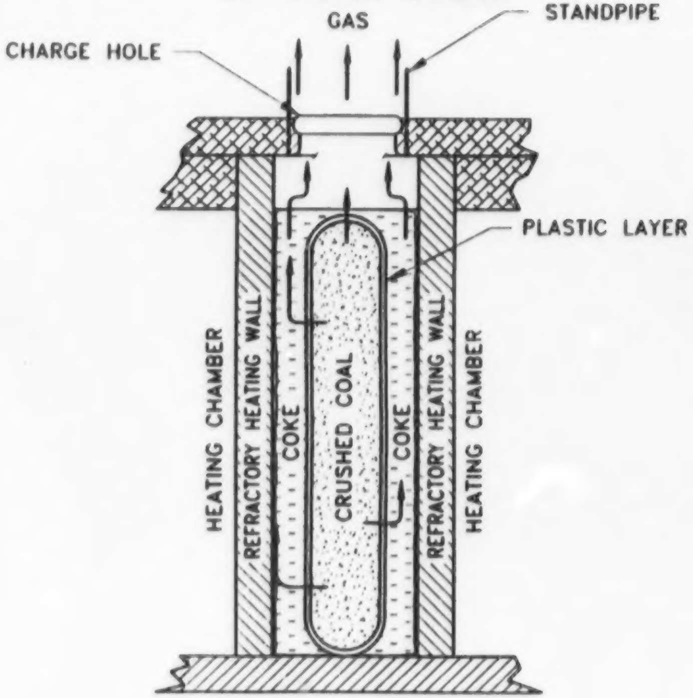
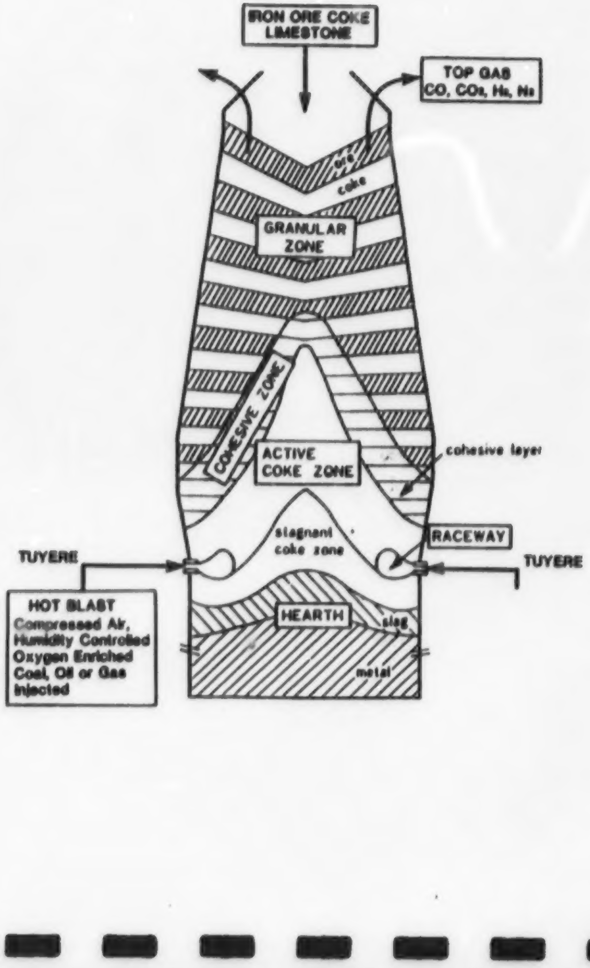

GAS
STANDPIPE
CHARGE HOLE
PLASTIC LAYER
HEATING CHAMBER
REFRACTORY HEATING WALL
COKE
CRUSHED COAL
COKE
REFRACTORY HEATING WALL
HEATING CHAMBER

FIGURE 8
BLAST FURNACE


IRON ORE COKE LIMESTONE
TOP GAS CO, CO2, H2, N2
ore
coke
GRANULAR ZONE
COHESIVE ZONE
ACTIVE COKE ZONE
cohesive layer
stagnant coke zone
RACEWAY
TUYERE
TUYERE
HOT BLAST Compressed Air, Humidity Controlled Oxygen Enriched Coal, Oil or Gas Injected
HEARTH
slag
metal

COKE QUALITY REQUIREMENT FOR THE BLAST FURNACE

In order for coke to perform the functions in the blast furnace described above it must be:

- high in carbon content and low in contaminating materials such as ash, sulphur, phosphorus and alkalies
- it must be of optimum size and have high strength properties to withstand the mechanical handling between the coke oven and the blast furnace as well as the weight and abrasion of the ore and coke burden as it moves down the blast furnace (Strength measured by various drum indices).
- it must maintain its strength at extreme temperatures (1500°C plus) and under severe chemical attack in the bottom of the blast furnace where coke is the only solid present (Measured as Coke Strength after Reaction and Reactivity).
- it must be consistent in quality, with minimum variability.

COAL PROPERTIES FOR BLAST FURNACE COKE

CAKING AND COKING PROPERTIES

Making strong coke is analogous to making strong concrete. Strong concrete requires an appropriately sized matrix of gravel and sand all bound together with the correctly balanced cement mixture. Similarly in coke making, for optimum coke strength, a proper balance between the coal's reactive and non-reactive carbon is essential. These constituents can be determined by petrographic analysis. The reactive constituents become plastic or fluid during the thermal decomposition of the coking process and provide the cementing material. The non-reactive or inert constituents have no fluid properties and provide the solid matrix.

The fluid properties of a coal are in part a function of rank (as determined by vitrinite reflectance) and in part a function of the inerts content of the coal, as well as the origin of the coal. The amount of inerts in a coal blend which result in optimum strength coke is also a partial function of rank.

Figure 9, the Japanese MOF diagram (Miyazu, T., et al. - NKK Technical Report), illustrates the empirical relationship between fluidity and mean maximum reflectance, for the key internationally traded coals. A target area for an optimum coke production blend has been defined by limits in fluidity and reflectance. Coals on the right hand side of the target area are required to maintain the rank of the blend, and coals above the target area are required to provide the necessary fluidity. Coals in the lower left hand corner can only act as fillers.

It can be seen from the diagram that primarily U.S.A. medium and high volatile coals can provide the surplus fluidity to offset the low fluidity of the western Canadian medium and low volatile coals.

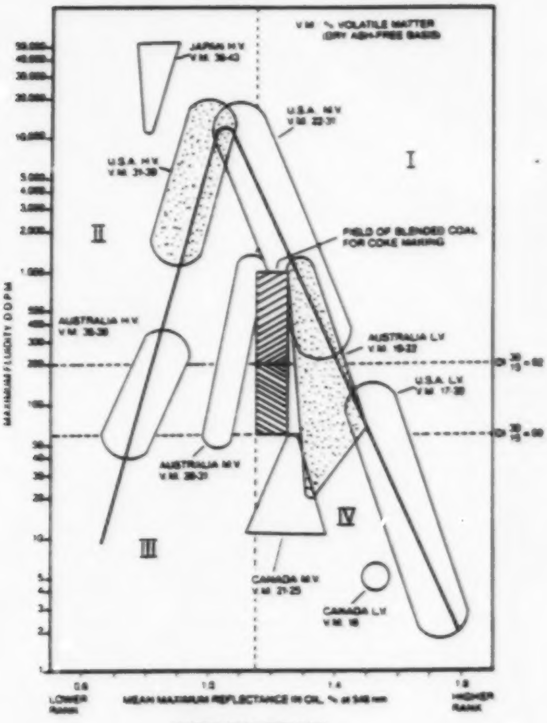
The differences in the plastic properties between the U.S.A. and western Canadian coals are illustrated by Figure 10. A study by CANMET, to explore the effect of petrographic composition on standard rheological properties, indicated that total dilation for western Canadian coal remained significantly lower than that measured for U.S. Appalachian coals of similar rank ($R_o$max - 1.22) and reactives (vitrinite) content. The difference in total dilation increased as the vitrinite content of the coals increased.

Geiseler fluidity showed similar trends; western Canadian values ranged from 10 to 200 ddpm compared with 200 to 10,000 ddpm for U.S. Appalachian coals of similar rank. These results, together with other CANMET test programs, suggest that optimum quality coke can be produced from western Canadian coals at lower plasticity levels, than for U.S. Appalachian coals.

The rheology differences between western Canadian and U.S. Appalachian coals appear to be caused not only by the different inert levels but also by the

FIGURE 9

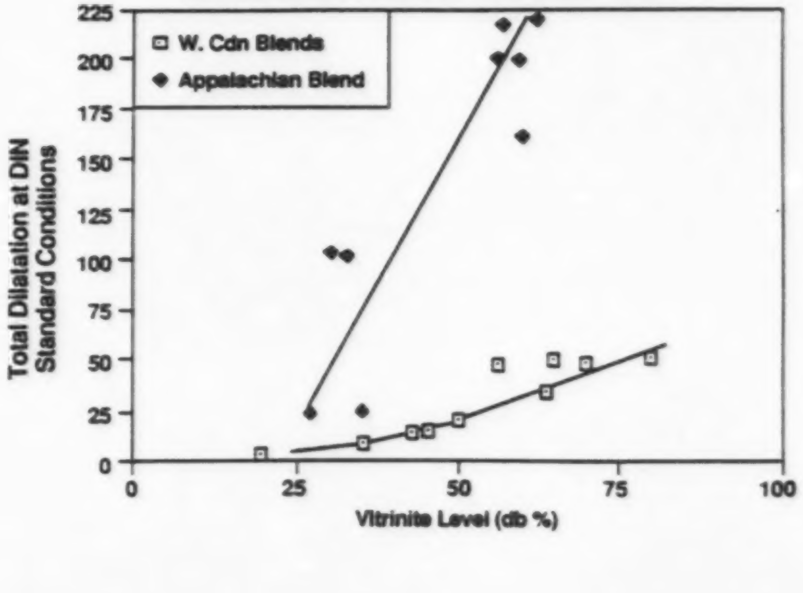
EXAMPLE OF COAL BLENDING FOR COKE MAKING



MOF DIAGRAM

FIGURE 10

EFFECT OF A CHANGE IN VITRINITE CONTENT ON THE TOTAL DILATATION OF A WESTERN CANADIAN AND AN APPALACHIAN COAL OF THE SAME RANK



chemical make-up of the vitrinite itself. The difference in chemical make-up is also shown by Figure 11 which is a comparison of volatile content and rank of western Canadian and U.S. Appalachian coals. It can be seen that for a given rank, western Canadian coal has a volatile content of 2 to 4% lower than the U.S.A. Appalachian coal. In coke making, this translates directly into improved coke yield (ie. lower volatile matter more fixed carbon).

OPERATIONAL PROPERTIES - COKE OVEN

For the conventional slot-type coke ovens described earlier, the refractory walls between the coking and heating chambers provide limited resistance to lateral pressure. As a result coal blends must be selected to limit the maximum wall pressure (as measured at a fixed bulk density in a movable wall pilot scale oven) to less than 2 psi or 13.8 kPa.

Coking pressure occurs as a result of gas being trapped inside the plastic envelope which forms along the sides of the oven chambers as the coal is being heated. Gas pressure built up inside the plastic envelop depends on the permeability of the plastic layer, and is transmitted through the coke to the oven walls. The peak pressure occurs as the two plastic layers meet in the centre of the oven (about 12 hours into an 18 hour coking cycle). Coking pressure is dependent upon charge bulk density, rank, inerts content and coking rate (Figure 12).

Many of the U.S.A. medium and low volatile coals and some of the Australian medium and low volatile coals exert strong wall pressures during the coking cycle. If this wall pressure is unchecked early destruction of the coke battery will result. On the other hand, the western Canadian coals generate much lower pressure and some in fact act as pressure moderators for high pressure generating coals.

Coking coals charged to the coke ovens, upon carbonization must also have certain shrinkage characteristics which will allow easy pushing of the coke. The high and medium volatile western Canadian coals exhibit excellent shrinkage characteristics and contribute to improved oven pushing and high coke yield.

OPERATIONAL PROPERTIES - BLAST FURNACE

Contaminants contained in coal, such as mineral ash, sulphur, phosphorus and alkalies, after carbonization remain, to a large degree, in the coke product. When the coke is charged to the blast furnace high ash and sulphur result in increased coke consumption and reduced blast furnace productivity. Excessive amounts of phosphorus impact negatively on the hot metal quality. High alkalies in the coal ash have a very detrimental effect on the blast furnace operation, causing hold-ups and slips as well as chemical deterioration of the coke as it travels down the blast furnace into the high temperature zone. Western Canadian coals tend to be higher in ash but are substantially lower in sulphur and alkalies than U.S. Appalachian coals providing a net benefit to a common blend.

Coke Reactivity and Coke Strength after Reaction (CSR) tests provide an indication of the deterioration of the coke in the high temperature zone of the blast furnace. There is a strong inverse relationship between reactivity and CSR. The presence of alkalies in the coke, has a detrimental effect on the CSR. Western Canadian coals have excellent CSR values as compared to U.S.A. Appalachian blends (Figure 13). While the CSR concept was first developed in Japan, it is now gaining wider acceptance in Europe and the U.S.A., supporting the increased use of western Canadian coal in these countries.

DEVELOPING TECHNOLOGIES

COAL INJECTION INTO THE BLAST FURNACE

One of the most important developments for the metallurgical coal industry is the rapid introduction in many countries of pulverized or granulated coal injection (PCI) into the blast furnace tuyeres. This technology is far from new, with commercial coal injection having been successfully practiced in the U.S.A. and China since the early 1960's. The technology was available much earlier, however, economics favoured oil and natural gas tuyere injectants. With oil price increases in the mid and late 1970's, tuyere injection was much reduced,

FIGURE 11

VOLATILE MATTER VERSUS MEAN REFLECTANCE
WESTERN CANADIAN AND U.S. APPALACHIAN COALS

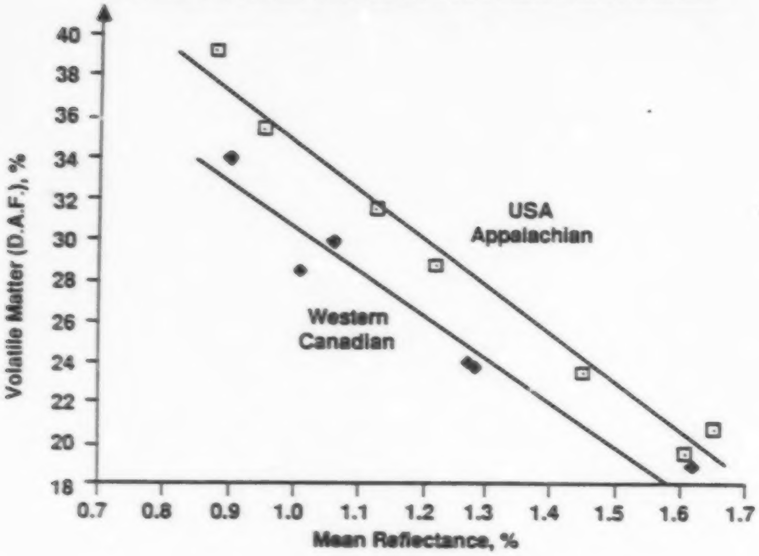
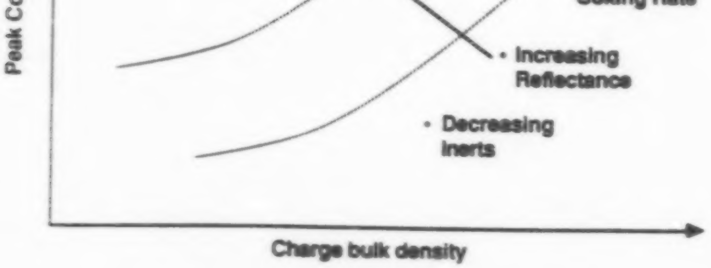


FIGURE 12

INFLUENCE OF KEY VARIABLES ON COKING PRESSURE


Peak Coking Pressure
Charge bulk density
• Increasing
Coking Rate
• Increasing
Reflectance
• Decreasing
Inerts

resulting in a less stable and less efficient blast furnace operations. This in turn encouraged blast furnace operators to turn again to coal injection. Coal injection provides the following advantages:

1. It improves blast furnace operating stability, fuel rate and productivity. It stimulates the reduction process and results in better gas distribution.

2. It permits the replacement of coke with less expensive non-coking coals. All types of coal from anthracite to lignite have been successfully injected. This assures long-term low energy costs. Coke replacement is a function of both coal and coke composition. Roughly speaking, 1 kg of medium volatile coal will replace about 0.85 kg of coke.

3. The cost of replacing coke oven capacity by coal injection facilities is 1/4 to 1/3 of the cost of adding or replacing coke oven facilities. Also, by using coal injection the loading of aging coke ovens can be reduced and their operating life can be extended.

Coal injection developments can be categorized by injection rate into three levels:

- 100 kg/Tonne of Hot Metal (THM) or less - requires minimal modification to the blast furnace operation, offers high flexibility on the choice of coal used and has limited impact on coke quality requirements.

- 100 to 250 kg/THM - is within the scope of existing technology but requires blast furnace modifications in hot blast temperature and oxygen enrichment. Coal and coke quality specifications are more stringent with respect to ash, volatile matter, (tending to lower vols.) coke strength and variability. Process stability is critical.

- 250 to 350 kg/THM - Implies an oxygen blown blast furnace. This is new technology. However, it is less complex than the smelting reduction process (discussed below) and has a shorter development lead time. This concept has the potential to increase blast furnace productivity from about 2 to about 3.5 THM/m^3/day. Coal, coke, and ore burden quality will be very critical for this process. Commercialization could be achieved before the turn of the century.

Coal injection to the blast furnace will continue to expand world wide. Coke quality will have to be improved and the split between coking and non-coking coal used, will be determined to a large degree by the ash burden in the blast furnace. Demand for low ash coking and non-coking coals will therefore continue to grow. The impact of this technology on Canadian metallurgical coal demand will be negative or at best neutral. Low ash non-coking coals can likely be supplied cheaper by other countries. Canadian prime coking coals however, can contribute to the production of the higher quality coke required. Some Canadian coking coals at present are being used very effectively in Europe as injectants. Here some steel mills have recognized the value of high carbon, low sulphur and low alkalies of the Canadian coals.

Table 1. below shows the growing importance of the pulverised coal injection practice.

Table 1. PCI Coal Consumption (1)

(Estimated in Million Metric Tons)

	1987	1988	1989	1990	1991E	1995E
Europe	2.1	3.5	4.0	5.2	6.5	9.9
Japan	2.3	2.3	3.6	5.2	6.0	9.2
Korea/Taiwan	0.1	0.3	0.8	1.1	1.5	2.3
Other						0.3
Total	4.5	6.1	8.4	11.5	14.0	21.7

(1) Messrs. Chardon and Barry; Sollac, France: Coal Injection: A Bright Future, presented at the 39th Canadian Conference on Coal September 15-17, 1991.

DIRECT IRON ORE SMELTING REDUCTION PROCESS (DIOS)

The Japanese DIOS Process is typical of a family of similar processes.

A schematic diagram of the DIOS Process is shown in Figure 14. Iron ore fines are pre-reduced 10 to 30% at 900 to 1000°C in the fluidized bed prereduction furnace using the gas produced in the smelting reduction furnace. The pre-reduced iron ore fines and coal are then fed to the smelting reduction furnace where molten iron/steel is produced at a temperature of about 1500°C.

The amount of coal required for the DIOS Process is essentially the same as for a coke oven/blast furnace operation. No coke is required in the process and a broad range of coals can be used. Nevertheless restrictions on ash, volatile matter, sulphur, alkalies, size, etc. still apply for optimum operation.

The DIOS Process has been designated a national project since 1988. Pilot scale work on a 50 t/day unit was completed in 1990. Work has commenced on the design and construction of a 500 t/day unit which is expected to start up in 1993/94. Operation will proceed for two years to 1995/96. Based on the 500 t/day pilot a commercial unit could be constructed by 2000 to 2005. Project scale up for the commercial unit would be the same as from the 50 t/day pilot to the 500 t/day pilot, ie. 500 t/day to 5000 t/day. The DIOS Process is seen as a swing producer in iron making with the blast furnace still maintaining the base load. However, by 2020 Japan could potentially produce 20 to 30% of total pig iron by this process.

OTHER DEVELOPMENTS

The following technologies and facilities have been developed by the Japanese steel mills over the last 10 years to reduce their need for prime coking coals and increase the use of cheaper and more abundant weak or non-coking coals. Some of these methods are also being adopted by non-Japanese steel makers.

1. **Straight additions to the blend.** Addition of weak coking coal to a coking coal blend is possible if the balance of the blend is "rich" in caking properties and would otherwise produce coke of unnecessarily high quality. The addition of weak coking coal in this way must be based on a detailed optimization of the blast furnace. Lower coke strength will increase the coke rate and reduce blast furnace productivity. The effect of weak coking coal on both the cold and hot strength of the coke complicates this evaluation further.

2. **Briquetting.** The bulk density of a coal charge and by implication, coke strength can be significantly increased by briquetting part of the charge. It appears that maximum density is achieved with some 30% of the charge briquetted. This improvement allows some 15% to 20% of weak coking coal

FIGURE 13

EFFECT OF TOTAL ALKALIS IN BLEND ON THE CSR PROPERTIES OF THE COKE

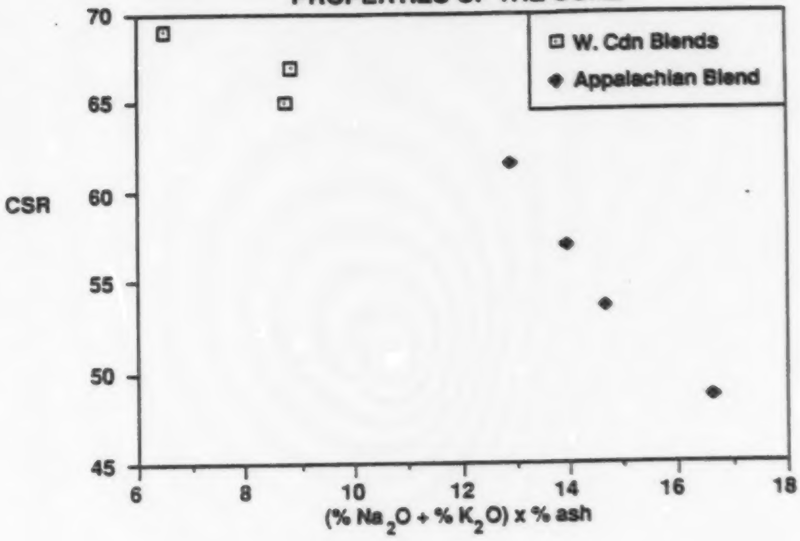


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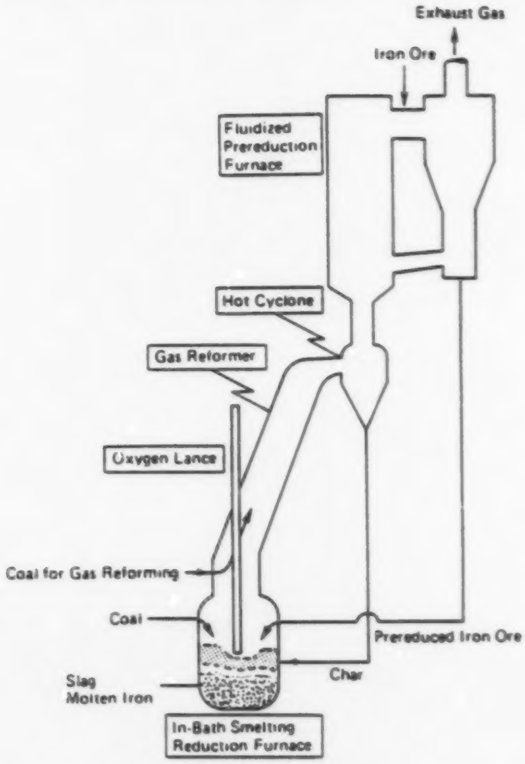
FIGURE 14

CONCEPTUAL DRAWING OF DIOS-PROCESS (Japan Iron and Steel Federation)


Exhaust Gas
Iron Ore
Fluidized Prereduction Furnace
Hot Cyclone
Gas Reformer
Oxygen Lance
Coal for Gas Reforming
Coal
Prereduced Iron Ore
Char
Slag
Molten Iron
In-Bath Smelting Reduction Furnace

to be incorporated although it seems to be unimportant whether it is included in the briquettes alone or throughout the blend. A special binder is required to produce the briquettes and this also contributes to the quality of the coke produced. However, this binder must have special properties and is consequently expensive. This factor and operating costs make briquetting unattractive and the equipment, only installed in Japan and Korea, currently is not fully utilized.

3. **Pre-heating.** By drying and heating the coal blend prior to charging, bulk density and hence coke quality can be improved. Productivity is increased by the reduced coking time. Weak coking coal can then be added at the rate of 5 to 20%, depending on the level of heating, to achieve the same coke quality. A level of drying to only 5 or 6% moisture may be economical today (Coal Moisture Control Process).

4. **Differential crushing.** Normal practice is to combine the different coals forming the blend and crushing them together. However, the different physical properties of the individual coals can result in harder coals being insufficiently crushed, with consequent deleterious effects on coke quality. Differential crushing prevents this by crushing selected blend components separately to the desired size range. (Western Canadian prime coking coals respond very well to this practice.) Any improvement can then be offset by adding weak coking coal.

5. **Dry quenching of coke.** Coke is usually quenched with water which causes severe thermal shock to the coke and reduces its strength by creating microscopic cracks. Dry quenching with gas reduces the thermal shock and improves coke strength. It also is an environmentally clean process. For the same coke quality 2% - 5% weak coking coal can be added.

6. **Formed coke.** This technology seeks to produce metallurgical coke from primarily non-coking coals. It has been demonstrated on a pilot scale that several process routes can produce acceptable coke. As the name suggests, the process involves the formation of a briquette of coal or char which is then devolatilised as a unit. There is as yet no evidence that this will emerge as a commercially significant process route.

CONCLUSION

Canada has a full range of excellent coking coals which have low sulphur, low alkalies and low variability. During coking they generate low oven pressures and make high stength coke.

World demand for coking coal is expected to grow at less than 1% per year. At this low rate Canadian coals will face stiff competition from other suppliers around the world and particularly from Australia. The increasing use of soft, weak and non coking coal made possible by new technical developments in coke and iron making will further increase market competition.